Development of micro tools for surgical applications

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A.A. 2002/2005
to Tom, the best teacher I ever had
Greetings

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Chapter 1
Introductory overview

This chapter introduces the thesis work: timing, keywords, glossary and the main specifications of the surgical instrument are described. These specifications, required to conceive a new instrument, informed all the research work.

1.1 – Thesis timing

The subject of the study is the development of an articulated mini-arm for heart surgery. The thesis has been developed in co-tutorship between the University laboratories PMAR Lab and LRP Lab, following this time scheduling:

- from 1/02/2002 to 31/01/2003 at University of Genova, (12 months)
- from 1/02/2003 to 30/11/2003 at University of Paris 6, (10 months)
- from 1/12/2003 to 31/01/2005 at University of Genova, (14 months)

Each main problem met during the development of this project has been discussed inside both the labs work teams. Thanks to the collaboration with the PhD student Damien Sallé, a prototype of the surgical instrument has been machined in Paris and tested (Chapter 7.1.4).
1.2 – Keywords
Surgical robot, Robotic surgery, Robotic surgery survey, Remote inspection and operation, Minimally invasive surgery, MIS, Laparoscopy, Laparotomy, Thoratomy, Articulated mini-arm, Endoscope, Active endoscope, Snake robot, Surgery gripper, SMA actuated gripper, Redundant manipulator, Control of redundant arm, Kinematics, Singularity analysis.

1.3 – Remote surgery
Scientific communities, Universities, private companies and some of the most important research institutes from USA, Europe, and Japan assume that medical robotics is a key field of research (Taylor03, Nagy03, Cepolina04a). Different applications exist: from eye surgery, to abdominal surgery, to prostheses and colonoscopies. The task of the robot is not to replace the surgeon, rather to support him with a set of instruments that simplify the procedures and reduce the patient trauma. Long since that robotic systems are used inside surgery rooms for minimally invasive robotic surgery (MIRS) operations.

Minimally invasive surgery (MIS) is an innovative approach that allows to reduce patient trauma, postoperative pain and recovery time. Aiming at MIS, miniaturization, safety and dexterity augmentation are some common topic of research (Cavusuglu01, Cavusuglu99, ComputerM04). For each minimally invasive operation, an endoscopic camera and from one to three arms are used. Today several surgical operations are accomplished using MIS; we focused our study on the hearth surgery, and more precisely on Coronary Artery Bypass Grafting (CABG).

The healing of surgical incisions is the main cause of post-operative pain. The goal of minimally invasive surgery is to reduce the size of the incision in the patient body while still providing proper visibility of inner-body details. The new approach replaces the wide incision used for classic operations with few small incisions. From these post-
accesses, through trocars, the tips of robot arms are inserted: an endoscopic camera and from one to three arms are used by surgeons to carry out the surgical procedures. The surgeon views the patient’s body through the camera and operates, guiding camera and surgical instruments from a remote position (Mack01). Each of the robot arms can be viewed as comprising two parts: outside the patient body there is the arm having several degrees of freedom; inside, a stick, carries a camera or a surgical instrument (Podsędkowski02). Modern surgical robots have a wrist interposed between sticks and surgical tools (Govindarajan01). The sticks have a diameter from 5 to 10 mm; this size is small enough to allow insertion between the ribs of an adult patient. The degrees of freedom of the outer arms are used to position and to orient the sticks, the wrist DoFs orient the effectors.

However, at present time, most of the existing devices used in MIS have limited dexterity, due to a small number of intra-corporal DoF. A neurosurgeon described the difficulties of operating with endoscopic methods: “It is like sewing a button onto a blanket cover in the bedroom through the keyhole of the front door with a pair of tweezers. In addition, the rooms are filled with a lot of furniture around which you have to lead the tweezers. But never knock anything over!” (Fatikow97).

This low dexterity is problematic for thoracic surgery, where only a few highly skilled and trained surgeons can perform minimally invasive heart surgery. Inside the human body, the workspace presents local constraints such as bones, muscles, organs and nerves; for example a stick, inserted between two ribs, has a limited rotation span (Podsędkowski02). Due to these constraints, several remotely overseen operations, like heart sewing or kidney exportation are quite difficult to perform. Sewing requires both wrist and arm dexterity and co-ordination. Kidney access is critical, since it is
surrounded by vital organs. The operation safety and reliability are greatly increased if
the stick is replaced by an articulated mini-arm and by considering task specific tools.
Several options have been studied to devise articulated mini-arms for cameras (Ikuta88,
Dario00, Hyo00, Ikuta01, Chapelle02, Kuhl02).

1.4 – The thesis aim

The thesis concerns the design of articulated mini-arms that can be used as surgical
instruments. The design of a robotic arm specially suitable for heart surgery operations
on an adult patient is considered. In case of heart surgery, the instrument is inserted
through a trocar, placed between two ribs. MIS surgery is tremendously demanding for
the design of surgical instruments.

The camera mini-arm and the surgical instrument mini-arm have to be both actively-
compliant to ensure high dexterity; only the surgical tool mini-arm needs to be heavy duty,
to develop and transmit the force necessary for the operation.

Figure 1.1 shows a new surgery theatre concept; the mini-arms are indicated by a red
circle. A service unit displaces, by means of a robotic arm, the mini-arms close to the
patient body. The design of the service unit will be carried out by the PhD student Silvia
Frumento (Frumento06).
1.5 – The surgical instrument specifications

The design of the surgical instruments has been driven trying to satisfy the requirements hereafter presented. In the conclusion (Chapter 8), it is critically assessed how much the proposed mini-arm satisfies each of these requirements.

1.5.1 – High mobility and dexterous workspace

One of the main drawbacks of the present surgical instruments is their limited number of DoF. For this reason today new robots able to guarantee more dexterity and appropriate workspace are under study; the final goal is to provide to surgeons, during MIRS, the same movement freedom typical of classic “open” surgery.

Increasing the number of intra-corporeal DoF could allow surgeons to perform heart and abdominal surgery more easily and thus allow these procedures to be performed by a higher number of surgeons. Introducing these extra DoF would also increase the
available workspace of the tools and thus could allow to perform procedures that cannot be performed today under minimally invasive conditions such as double or triple coronary artery bypass grafting (CABG).

1.5.2 – Miniaturization

The mini-arm has to present very small cross-section in order to comply with the minimal invasiveness specifications. The maximal inside diameter of this trocar and thus the maximal outside diameter of the instrument has to be limited to 10 mm.

A limited weight and the possibility of internal cabling are useful but not mandatory features. Use of embedded Micro Electro Mechanical System (MEMS), with force-actuation and shape-control are good properties. MIRS instruments, like grippers and scissors, need to be as compact as possible.

1.5.3 – Versatility

The surgical environment asks for instrument versatility: in fact the environment is usually unstructured and each task and its execution are specific for each patient, furthermore the work has to be done on a human being with tissue with different softness.

Moreover the fixture has to adapt to different surgical procedures and be endowed with the pertinent effectors. The possibility of a quick and automatic end-effector changing device is a good characteristics that allows to shorten the surgical procedure. Specifically task-oriented end-effectors are considered, e.g., a self-operating sewing rig, able to operate with a single thread. Examples of laparoscopic surgery tools are; scalpel, scissors, electrocautery scissors, video camera, graspers, syringe, needle driver, sewing machine, electrosurgical J-hook and tissue dissector.
1.5.4 – Modular architecture

Modular architecture has to be preferred both for aim of reconfigurability of the arm in order to adapt to different surgical procedures, both to enhance maintainability in a life cycle approach.

Modularity allows easy modification of the instrument topology. Following the previous considerations, actuation modules with one or two DoFs are considered. Figure 1.2 shows some module schemes; a module is represented by a rectangle and its interfaces are applied to the shorter sides. The arrows show the direction of the actuated DoF.

![Figure 1.2 – Modules schemes.](image)

Standard interfaces provide the mechanic, power and signal link between the modules.

Following this modular approach; the instrument may be formed by a suitable sequence of actuation modules carrying, at the end, a surgical tool. To enhance the system modularity, each module of the mini-arm should be provided with independent actuation and control; for the same reason, the surgery grippers should be conceived as interchangeable end-effectors.

1.5.5 – Operative performances

Because the surgical instrument works under the surgeon supervision, by tele-manipulation, accuracy is very important but not the main concern; arm stiffness and
error compensation are the main features able to guarantee accuracy. Manipulability and reliable and robust vision feedback are main requirements; the surgeon performance will improve thanks to force reflection.

The development of a teleoperated robotic system with force reflection capabilities that can control the tool motions and tool-tissue interactions via the feedback to the user through the man-machine interface will provide a precious sense of touch to the surgeon.

Experiments have been carried out by surgeons using sensorized instruments, to record force and position data during a coronary artery suturing procedure. Experimental values are: artery perforation force 0.5 N, wire stretching 1 N. For this task, a needle is placed in a gripper. From microsurgery literature, gripper force must be larger than 4N to hold correctly the needle (Peirs98). 40 N is recurrent value for needle holding force for endoscopic robotic systems (ComputerM04).

1.5.6 – Safety, dependability

Safety, reliability, availability, confidentiality, integrity and maintainability are the six attributes of the concept of dependability. These concepts are becoming critical for personnel and human interacting robotics.

In medical robotics safety is a key factor and it has to be pursued at all levels in order to realise intrinsic safe surgical instruments: at the level of interaction with patient and at the level of interface and cooperation with the surgeon.

In our case, intrinsically safe robots will be considered. Intrinsically safe here means that safety constraints are handled as soon as the design of the robot is started.

Intrinsic safety constrains many choices about the components and the mechatronic and
control system architecture.

Various components contribute to guarantee the safety of the active mini-arm:

- Actuators with limited power and/or speed which guarantee safe behaviour in case of fault;
- High reduction gears such as harmonic drives contribute to safety design; but high reduction ratios leads to irreversibility which can be a drawback in case of emergency procedures;
- Dead Man Switch (DMS) pedal, used by the surgeon to validate the task execution in automatic mode;
- Mechanical torque limiters in the joints improve the safety margin.
- Parking brakes on joints prevent the robot from collapsing when the power is off;
- Absolute sensors in each joint give always reliable position reference;

From the control point of view

- A watchdog board has to be included in order to manage the security. E.g. if the effort exerted on the end effector exceeds a given threshold, the watchdog is immediately deactivated and the power is switched off as well.
- Redundant circuits wired on the board improve security;
- Software joint limits have to be implemented;
- The multiple configuration problem of the arm has to be prevented in both position and force control modes. The knowledge of robot singularities is very important in order to allow the control system to drive the robot trajectories continuously and smoothly.
1.5.7 – Redundancy

Redundancy may concern hardware components such as sensors, as well as software. Increasing information by redundancy should reduce risks but some major disadvantages may be underlined: firstly, the cost is increased, secondly, increasing the component number increases the complexity of the system, which finally decreases its reliability.

1.5.8 – Body compatibility

The main requirement of the surgical min-arm is not to damage the human body in terms of used material, ergonomy and cleanliness. Each component of the system must be sterilizable. This clinical constraint may be satisfied also by covering the mini-arm with a sterile sleeve while the end effector tool has to be sterilised by an autoclave procedure.

1.5.9 – Easy control

The mini-arm is driven in teleoperation by the surgeon who in general is not expert in robotics. The use of the instrument has to be as easy and intuitive as possible in every operative mode (insertion, sewing, emergency...).

Easy and user oriented control system will enhance the instrument reliability and surgeon capabilities so improving the task execution performances.

All the control algorithms needed for safety reason have to be hidden to the user who will receive only high level and easy readable information about the state of the active apparatus and the surgical procedure progression.

Operative performances of a non-linear, environment interacting instrument, like the surgical mini-arm, will be greatly improved by introducing kinematic and dynamic
effects compensation logics that allow the avoidance of singularities, the gravity terms compensation and the decoupling of cross effects between modules. Such control logics, based on the deep knowledge of the instrument, even if introduce new cumbersome algorithms, will simplify the teleoperation tasks to the surgeon because the different modules will behave as almost independent and problem of singularities will be faced at the instrument control level that is transparent to the surgeon.

During the operation, the tip of the end effector shall reproduce faithfully the surgeon suturing movements, while the wrist should not touch any organ or tissue; arm stiffness and error compensation are the main features able to guarantee accuracy. If, for any reason, the robotic aided operation fails, the surgeon should be able to remove quickly the robot and continue the operation using more classical instruments; fast modules retrieval is then a key feature.

1.6 – Organization of the thesis

The thesis is organised in eight chapters.

The first chapter gives an overview of goals and introduces the new concept about the surgery room and the surgery mini-arm. The state of the art general concepts and trends are summarized in chapter 2.

A great effort has been made in the state of the art search either in the robotic surgery either in the actuation technology. A discussion of the proposed mini-arm surgery tool is anticipated and compared with other solutions in chapter 3. Different technologies for miniaturised actuation are illustrated in chapter 4.

Chapter 5 addresses robotised surgery typical problems and presents some early design solutions.
The main PhD research results are presented in the chapters 6 and 7.

The design process of different surgical tool modules are presented within chapter 6 from the basic concepts till the detailed design phases. Different options are studied and the related basic operational characteristics are summarised and compared. For modularity reasons, all the tools are connected to the articulated arm using the same interface. First some possible solutions are analysed and compared. Then the detail design of the preferred embodiment is described; a physical mock-up has been used to check the tool performance. Advantages and drawbacks of the system has been pointed out. Finally some possible system implementations are suggested. For each module digital mock-ups are given and main technical characteristics discussed.

A selection of the designed modules has been realised as physical mock-ups and prototypes; they have been assembled in a redundant serial kinematic chain. Control issues of this surgical tool are then presented. A multi-level control system is proposed based on the robot non-linear models. Parametric kinematic and singularity analysis models have been written, tested and checked; the relative modules should be integrated into the control system. The dynamic model and simulation of the surgical tool behaviour in a realistic environment, using ODE libraries, is also proposed. All these aspects are included in the chapter 7.

Conclusion and issues about future work are the subject of the chapter 8. The design work and the new instrument realization were oriented to the given specifications but sometimes economical and/or technological constraints did not allow the complete fulfilment of these requirements. In the last chapter the obtained results are discussed with reference to the requirements specified in the first chapter.

The datasheets of the main commercial components used to create the prototype are
resumed in the appendix A.

The technical drawings of some mini-arm modules are collected in the appendix B. Not all the constructive details and modules are presented even if this work took a lot of effort and time but the scientific relevance is poor and moreover some confidentiality constraints apply.

Appendix C includes the main software modules (written in Maple), implemented to calculate the instrument workspace. These modules, for sake of generality, are written in parametric form and can be used for different applications and scale of the same selected robotic architecture.

The behaviour of the proposed mini-arm can be simulated thanks to a software environment purposely developed (Appendix E).

The control, written in C++, avails of Open Dynamic Engine libraries (Appendix D).

The suggested reading modes are represented in figure 1.3.

![Figure 1.3 – The thesis suggested reading diagram](image-url)
Chapter 2

Robotic surgery: concepts & trends

Robotics has pervasive spreading in every day man life, as it provides options highly enhancing the access to exacting functions with wider capabilities and higher performance. This general axiom is valid for surgery, as well, which requires the on-site presence of agents with twofold bent “recognition-and-intervention” in view to accomplish finalised tasks, with intelligence of the on-progress operations. Such premises are common demand in instrumental robotics, where effectiveness is given by duty-driven solutions, suitably balancing material-and-information handling.

The robotics achievements in medicine (Taylor03, Cepolina04a), thereafter, follow complementary tracks, encompassing:

• task acknowledgment, by process-data acquisition and diagnostic features assessment
• task execution, by operation sequencing and adapting by work-progression monitoring under surgeon’s steering, according to direct, either, remote supervision and control.

The robot aids improve and widen information and operation bases, with noteworthy up-grading of merely human capabilities.
2.1 – Towards MIRS

The up-grading in robotics is technology-dependent, by the traditional role of mechatronics and ICT, and by the still undisclosed possibilities of nano-technology. Surgery, up now, basically moves within the scale of man visual and tactile discrimination; standards in-body interventions require deep and large cuts, to create an operation foreground accessed by sight and by hands; recovery is highly affected by these side requirements, in spite of the impressive advances of modern medicine.

Robot surgery will, indeed, provide turns similar to what done by machine-tools manufacture after handicraft. Artificial effectors are made available, with miniature size, even below standard human handling scale. The operation theatre is accessed, directly, by percutaneous needles, or, through trocars, by articulated rigs, carrying tools; the action is monitored by local miniature cameras or through TAC/RMN images of externally located devices. The surgeon is required of remote governing, by master-slave command of the carried tools, following operation protocols, which might, eventually, transfer in charge to the robotic devices the autonomous accomplishment of pre-set sub-tasks.

Instrumental robotics aims at providing function-oriented solutions for given technical problems. Micro-Electro-Mechanical-Systems (MEMS) technologies supply miniaturized instruments, capable of effective duty-cycles at millimeter ranges. Several MIRS devices exist, developed for intracorporeal operations; - system architectures, mainly concerned with problem-solving approaches and synthetic outlines of modified methods and layouts. The thesis is principally concerned with technologies, but the nature of the medical surroundings cannot be disregarded. Robotic devices serve surgical staff to help them accomplishing surgical procedures. Safety and reliability require high functional and structural performance, especially for the active, autonomous stages of the operation. All these aspects need to be considered during the design phase.

Computer-assisted surgery expands as technology-driven option, to encompass: - passive aids (navigation and aiming devices, enhanced restitution displays, etc.); - supporting aids (action guided interventions, based on previously defined strategies,
finally enabled by the surgeon); - autonomous aids (task sequences performed by the
robot, under the watchful eye of the surgeon). Data infrastructures basically supply
enabling procedures to the feasibility of autonomous or co-operating aids. The
execution effectors aim at replacing the tangible efforts of human operators, with
benefits as for accuracy, delicacy, dexterity, efficiency, safety, size, versatility, etc. once
the instrumental properties are optimised (and anthropocentric limitations are overrun).

The focus on execution effectors draws attention to the quick evolution in the nano-
technologies; they will, probably, deeply modify to-day instrumental aids. A survey
(Chapter 3) to review some available means is, therefore, useful mainly to specify
underlying concepts and functional modules in view of future issues.

The robots are enabling support of the minimally invasive surgery, MIS, the technique
aiming at localised interventions, with negligible side effects. Today, only pioneering
steps are moved, as compared to potentials, as robotic aids are at an early stage and
reliable protocols need establish on fully acknowledged experience. In chapter 3,
comments on technological issues are given by means of explanatory examples, showing
options and trends from an engineering point of view.

Surgery robotics, according to recalled frame, needs move by pace-wise changes of the
assessed techniques, showing feasibility and benefits of new ways to solve given
treatment problems. Simple hints directly appear, once the MIS alternatives are
acknowledged (Temple04), say, for instance:

• open surgery: opening technique; operation sequences and protocols; suturing:
absorbable, non-absorbable, synthetic, non-synthetic; knot tying: hand ties, instrument
ties; wound closure: simple interrupted, continuous, mattress, sub-cuticular, skin staples;
anastomosis: bowel (single layer, two layers, stapled), vascular; etc.;

• MIS surgery: trocars placement; closed (Verres needle), open (Hasson technique)
abdominal access/pneumo-peritoneum; endoscopic suturing: interrupted, continuous;
endoscopic knot tying (infra/extra corporeal); endoscopic drills: peg board, cup drop drill, rope-pass drill, pattern cutting, anastamosis bowel, ligature; endoscopic troubleshooting; etc..

Tools in the approach, accordingly, evolve from conventional scalpels, scissors, needles (cutting, tapered, blunt, etc.), needle drivers, forceps, haemostat staples, etc., to trocars, endoscopes and endoscopic towers, dissectors, graspers, harmonic scalpels, endo-clips, endo-GIA, etc., with clear separation of execution from information infrastructures.

There are at least two problems common to many robotic surgical systems; cost and space. Only a limited number of hospitals can afford, for example to buy and to keep operative a da Vinci™ system. Moreover, these devices are large; often a whole operating room has to be dedicated to auxiliary equipment. The study of simpler and smaller contrivances is a challenging prospect. Before turning back to alternative surgical tools, which can enable highly innovative procedural protocols, a short reconsideration of the operating environment is useful.

### 2.2 – Surgical theatres/procedures

Robotized surgical procedures are typically based on the availability of a set of instrumental aids to assist and to perfect man’s actions through any specific operation. These procedures need to cover the four phases: mapping and diagnostics, scheduling and planning, supervision and tracking, completion and assessment. Each phase requires suitable equipment and integration means that an information framework keeps the data consistent. On such premises, procedural innovation will combine new devices, with new protocols. The preparatory phases require the careful mapping of the theatre and the accurate planning of the task. Today data acquisition uses non-invasive instruments and sophisticated analysis to compare issues and to perform diagnoses. Task planning
can make extensive use of simulation and virtual testing carried on digital mockups. Ultimately, full 3D models are available, furnished with task schedules and timings and equipped with risk analysis and change suggestions. Graphical reconstruction techniques are now well developed, assuring enhanced accuracy pictures, with size and shape preservation of every relevant detail. Thereafter, the robotic aids are enabled to provide real-time, on-line, dynamic support to the surgeon. Supervision is enabled by endoscopy, while task tracking makes use of remote control, filtered and extrapolated by the robotic interface. The accomplishment of the task can be delegated to autonomous work-cycles as the case arises, and in the event of any unexpected occurrences, the surgeon can resume control of the task. In summary it is now possible, for the various sources of information, to be combined into an integrated system.

Aiming at replacing the surgeon’s manual capabilities, lots of studies have focused on handing mastery and skill, or generally supplying problem-solving technologies. These studies must consider the task peculiarities:

- the operation is performed on a human being: the working conditions never repeat (body size, organs setting and shape, position on the operation table, incision point accessibility, soft tissues characteristics, nursing scopes, etc.);

- the surgeon is not a robot specialist, but issues of responsibility cannot be shared with non-medical staff: user-friendly man-machine interfaces are critical. The instrumental aids, thereafter, need grant complete transparency up to the supplied function, with no bias of mechanical couplings;

- reliability and safety need to be established as intrinsic properties: trial and error or re-do procedures are not allowed when the robotic system is in contact with the patient;

- mapping and diagnostics are preliminary steps of the integrated task;
virtual testing on digital mock-ups is an enabling opportunity: scheduling and planning are off-line procedures, to create redundant knowledge and to anticipate possible complications;

- the protocol’s redundancy enhances versatility: real time plan up-dating, according to on-line diagnostics, will comply with patient behaviour and accommodate unexpected complications;

- the procedures delegated for autonomous accomplishment are monitored, and the surgeon can stop or modify them at any time;

- the manipulator and related end effectors are only additional instrumental aids: the operating room is cluttered by several other medical aids (radiology, anaesthesia, etc.) and balanced integration is a critical issue;

- additional attributes characterizing medical robots dependability: safety, reliability, availability, integrity, maintainability, versatility, flexibility, confidentiality, transparency, etc…

To that scope, a surgical device has always to comply with overall demands: no uncontrolled motions; bounded output forces/displacements; self-recovery end-effectors; constant surgeon’s overseeing. A robotic set-up should be conceived and built according to well-known principles: high degree of redundancy in sensing, actuation and control, in order to enable pro-active maintenance; proper inclusion of intrinsically safe components and procedures, to reach negligible risk of equipment failure; balanced integration of the instrumental and the information equipment, combined to provide a task specific solution.

Now, micro-robotics is quickly expanding the field, with innovation brought in by nanotechnologies. Robotic neurosurgery operations date back to 1987, when Kall and Kelly, in the Mayo Clinic, used a laser beam which was directed towards the target by two computer-controlled galvanometer mirrors. For surgical operations the actual size of
fixtures is a problem. Nanotechnologies are expected to bring in noteworthy benefits. The advantages in the medical field are evident. Microsurgical robots will lead to reliable, safe and repeatable procedures, with less pain and trauma, and reduced recovery times. In the near future, changes will not aim at removing front-end surgeons, rather at progressively lower invasiveness, properly exploiting innovative devices and seeking new techniques that might drastically modify treatment practices. In such a context, simple details might provide relevant improvements.

2.3 – Organisation & technologies

A robot conventionally is characterised by a serial or parallel arm (and pertinent tools), so that the tip work-space is acknowledged and ruled through the actuation joint-space. The in-body work-space, accessed by locally constrained paths (e.g., trocars), is encumbered with obstacles (say, connecting tissues) and blocked up with forbidden zones (say, vital organs). The initial design request is: how many actuated joints lead to a 6 DoF tip? Conventional analyses show how to oblige a mini-arm to slide along a space point (trocar location), with fixed slope (trocar inclination); alternatively, with sensors on the trocar, and feedback acts on the mini-arm mobility, to keep a fixed position and slope. It is more questionable to deal with in-body restraints, as the vital organs modify shape and size and the intervention point needs to adapt to changing conditions; the pre-selection of an optimal mini-arm path is only a possible guess to start with; the resort to local displacement or pressure sensors requires critical observation gauging and path planning steps to deal with uncertainty.

Robotic operating procedures require poly-articulated devices, whose shape needs to be controlled to follow curved paths; high priorities are miniaturization, for lower impact on living bodies and availability of reliable dexterous effectors. The overall requirements lead to redundancy in mobility, sensors and control and to recovery in function, actuation and intelligence.

Basically, instrumental robots characterise because of: - function bent pre-setting; - task
programming and up-dating; - duty progress monitoring; - surroundings overseeing; - autonomy management within allowed specifications (ComputerM04, Imperial04). This robot is required to work inside properly structured bounds; still, the environment, it is interacting with, belongs to alive matter, and might quickly turns to drastically different situations. Thus the changes need to be acknowledged, the emergency plans and safe recovery shall be autonomously enabled, all information should be displayed to the on-duty surgeon, with, possibly, hints for subsequent steps. The proper setting of autonomy limitations is subtle question, and, in any case, trimming to individual whims or complete overriding needs to be possible.

Out of these general features of robotic surgery, robotic surgery is a technology-driven opportunity, specially, in two domains:

- information infrastructures: data acquisition, handling, vaulting, transmission, validation, processing, etc. are continuously expanding options supported by the ICT, and effective new computer tools ceaselessly appear to support remote supervision and control. Tele-medicine is fully acknowledged technology, while remote-surgery has only experienced noteworthy accomplishments;

- execution effectors: specialised tools and fixtures are the most challenging research incumbents, possibly, today, too much tied up with human handling scale. In the future the surgeons shall continue to deal with standard sizes; the inner-body interface will timely evolve toward micro- and nano-apparatuses, as soon as effective new solutions are conceived and made available.

The survey presented in chapter 3 is considering topics in this second domain, looking at lay-outs, with intrinsic effectiveness and attention on the fact that the merging between information and material flows is characterising feature. MIRS, represents critical improvement of MIS, by removing the direct link “instrument-surgeon” and related mobility and flexibility bounds through trocars or per-cutaneous barriers, and by enabling remote control by master-slave techniques or other equivalent settings.
Today, only five options are used to actuate miniature surgical apparatus:

- miniature DC motors, ranging from 1.9 mm diameter in which reduction is obtained by planetary or harmonic drive gearboxes but usually the power/volume ratio is limited;
- cables with opposing springs whereby simple actuators provide a homogeneous power supply to the effectors; size limitation is the principal drawback;
- shape memory alloys are a really popular option but the biggest hindrance are hysteresis and time delay, as the switching requires certain temperatures, that are reached by heat exchanges controlled by (small) electrical power sources;
- piezoelectric materials are quite a reliable opportunity but actually limited by tiny overall power and comparatively small induced strains;
- electrostrictive polymer artificial muscle: innovative technique requiring further assessment.

### 2.4 – The split duty approach

Moving on along the recalled lines, robot opportunities are mainly technology-driven aids that need shared acceptation and appropriateness, to enter into common practice. Indeed, implements are but at preliminary steps, and impressive innovation is expected by nano-science outcomes, for front-end sensing and actuation devices. Still, the instrumental assistance requires revising assessed habits in existing protocols, looking after a different surgeons’ involvement, little by little less urged to reach the highest skill in manual dexterity, progressively required to co-ordinate multiple tasks and to defer front-end interventions, simultaneously done by co-operating end-effectors.

MIRS, thereafter, is believed to move towards developing specialised co-robotic devices, to be integrated, based on selected functions, in the operation work-plan, in keeping with the abilities assigned to the individual rigs. A previous analysis, accordingly, needs to be carried to distinguish these functions and to assess some standard operation
settings, so that the new technologies are included into already acknowledged contexts.

By the split-duty approach, the mini-arm selection process considers to programme, separately, carriers and effectors. Several competing lay-outs can be dealt with, but, in general:

- the carriers are conventional arms, with distal rigs held, controlled in position and attitude, near by the patient’s body;
- the effectors are mini-arms for in body interventions, possibly, articulated to assure convenient insertion and shaping.

A hierarchic controller manages the all; the carrier position and attitude are initially set and, thereafter, tuned, depending on effectors requests, along with duties progression. The split-duty aims at optimality, considering as primary instance the effectors’ requests (based on the fusion of sensors data and visual checks), with secondary falls-off on the mini-arm set-up. The split-duty approach quite naturally leads to modularity. The auxiliary handling frame can readily exploit standard arms, up to a rigged-out platform, carrying the special end-effectors and related feeding and controlling interfaces. To design the MIRS environment, thus, typically means considering the development of dexterous devices with front-end in-body tools.

Following to these concepts, the characterising modules of the end-effectors will cover:

- the platform plug-in module, for latching/unlatching actions and power/control lines connection;
- the holding modules, to provide correct insertion in the patient’s body, as for location and attitude;
- the in-body modules, to grant proper reach to the operation theatre, through a safe path.

Only the last modules request pressing needs for sterile and miniature components; a safe and fast (bayonet, etc.) coupling could be devised, to link/disconnect them from the other modules.

The modular design concept simplifies the build-up of the useful redundancy. Basically,
in-body mobility is, today, quite limited. The simplest set-up aims at a needle, through a per-cutaneous notch, suitably directed to the entry location and along the best path slant. Slightly more sophisticated arrangements deal with 10 mm diameter rods (Cepolina03), inserted through trocars; at the front, a 2 DoF wrist and 1 DoF tool are driven, most of time, by cables actuated by off-body motors.

The resort to articulated probes has been considered, often for endoscopy and specialised (laparatomic, gynaecologic, etc.) interventions (Cepolina04a). The constraint on mobility aims at making the operation feasible, disregarding the (more or less relevant) side-effects; invasiveness is lowered, but not avoided, when vital organs are involved. An articulated in-body probe has higher dexterity with modules higher in number and smaller in size. Cable-actuation quickly faces unavoidable drawbacks, due to modules force-coupling. Happily, current micro-electro-mechanical technology already provides effective means to obtain better arrangements.

The overall redundancy is turned to satisfy separate requirements, depending on the timely addressed task assignment. Force feedback from the operation interface, (trocars and effectors) friction compensation, shape up-dating for proper engagement, etc. are added opportunities, offered to the surgeons as case arises, while a routine progression might deploy with continuity upon their consent, following standard rules.

An effective MIRS set-up will allow:

- tactile feedback, to appreciate the touched items compliance;
- kinaesthetic restitution, to fully govern the grasping/handling forces;
- 3D visualisation, to support correct hand-eye co-ordination;
- 6 DoF manipulability, to supply full dexterity for in-body actions.

The four functional requests need integrate technical frames, built on: - end-effectors path/mobility redundancy; - intelligence for autonomy management; - operation reliability and intrinsic safety; - on-process diagnostics and self-recovery. These achievements basically exploit virtual reality restitution and behavioural emulation: realistic imaging, duty-cycle assisted progression, intuitive/ergonomic interfaces,
automatic monitoring and completion of pre-set tasks, etc.; new intervention techniques and protocols will develop, depending on timely available technologies.

Reliability and safety are MIRS preliminary demands, as interventions: apply on human technology offers twofold winning extension to MIS: due to its inherent handling effectiveness and remote control abilities, due to the functional extensions of the carried end-effectors abilities.

The anthropocentric approach eventually mixes the two abilities, as accuracy, dexterity, handling, sensitivity and versatility are compared to conventional surgeon’s expertise. Again, instrumental hardware components will be considered, but analogous concepts are present for software supports. These aspects should, first, distinguish basic properties in the architectural lay-out (the prospected split-duty approach, to separately address mini-arm handling and effectors duty), from the evolution of the main technologies (to keep the pace of innovation by carefully looking after desired functions, through modular built-ups). Again, these hints are merely a spur to foster discussion, but proper acknowledgement of typical robot features seems a factual way to provide suggestions to innovate, specially, in these medical fields.

Different robotic architectures and operation strategies might be devised, such as the split-duty approach. This characterise by distinguishing: the service unit, granting the positioning and feeding of the MIRS set-up; the front-end effectors, performing the in-body access of tools and cameras. Each sub-system is hierarchically governed by a remote location, following effective protocols, while the interfaced operators receive the sub-set of information at the selected degree of immersion, with suggestions of consistent (vs. not advisable) actions.

The split-duty approach can expand at different levels of sophistication. In general, it follows the concept of functional allocation and structural modularity, to manage redundancy, enhance reliability and grant safety. The final lay-out aims at provisions duplication by preserving leanness.
Chapter 3
Robotic surgery: noteworthy devices

Robotic surgery appeared as technology-driven innovation, but actually is recognised to represent factual challenge to improve healthcare effectiveness. This chapter introduces to current trends, using a few examples as explanatory reference to distinguish the basic options of robotic devices, from remote handling, to on-process intervention.

A robot is a function-oriented item of equipment, capable of accomplishing the required tasks with a proper level of autonomy due to the embedded knowledge of its surroundings. This definition properly encompasses instrumental robotics, and develops along the lines of one so-called axiom of robotics, namely: “if a complex task is fully understood, an apparatus can be devised and built assuring its effective accomplishment”. The approach considerably differs from anthropomorphic robotics which possess the property of emulation and the capacity to mimic human solutions. Human behaviour represents one way to discover a method to assure task fulfilment; this typically leads to solutions where the physical sizes and required forces, consistent with visual detection, reach and manual dexterity, etc., are within anthropomorphic scales. The human simulation approach considerably restricts the available solutions and becomes particularly penalizing when very large or very small scales are involved.
Minimally invasive surgery requires innovative solutions when miniaturized equipment is required for operating procedures beyond the reach of eye and hand. The use of instrumental robotics provides stimulating opportunities, which can only be realized when an accurate description of the method is linked to a thorough understanding of the possible instrumentation. The introduction of robots in medicine has perhaps not yet achieved its full potential because the relationship between doctors and patients is a delicate one, which is partly dependant on reliable knowledge of prognosis and care. Nevertheless sophisticated medical apparatus are continuously being developed, providing valuable aids to accomplish clinical tasks which were not previously considered possible. This chapter describes the instrumental devices specifically conceived as surgical instruments with a focus on the new Micro-Electro-Mechanical-Systems (MEMS) technologies. MEMS are a rapidly evolving concept assuring a variety of functions such as surgeon’s assistant, remote sensing and vision, autonomous activity etc. The miniaturized equipment is task specific and designed to accomplish the assigned actions which are beyond anthropomorphic limits, while remote monitoring visualizes the procedure. On this basis, the field of instrumental surgery robotics becomes very large, encompassing handling fixtures (to replace hands and related manipulation and sensorial capabilities), and different sensors (vision, etc.) and end-effectors (probes, etc.). The research is primarily concerned with the available instrumentation for robotic surgery, and for each apparatus a short description of some examples and some images are provided. The description is intentionally short, to provoke the reader’s interest, therefore, for a fuller understanding the quoted references should be consulted. The selection of the examples is by no means exhaustive and only introduces noteworthy aspects that help to enhance the wider applicability of task-specific set-ups. The analysis of current surgical aids provides descriptions of current problems and suggestions about how worthwhile innovations may have their effectiveness extended. The review ends by comments on how to exploit existing trends, with due account of pace-wise progression in MIRS.

The examples prospect explanatory hints to show actual or feasible rigs that robot
technology provide for accurate localisation and scanning, for safer endoscopic trials, for specialised (urology) surgery, for better execution effectors, for futuristic treatments and for supporting aids.

The example selection comes out of a state-of-the-arts study, accomplished to sketches domain trends, from open surgery, through minimal invasive interventions, to non invasive treatments. Robotics, in such a context, means moving from requiring the surgeon’s active involvement (tools driven by humans), to look after hybrid set-ups with man supervision of properly autonomous devices. These needs include sensors (for advanced diagnostics, such as TAC and the likes; in-corpore testing, urea, pH, glucose, K+, Na+, Ca++, etc., temperature, heart beats, pressure, etc. local measurements), and actuators (centralised vs. decentralised lay-outs; cable-driven settings; electro-magnetic, piezo-electric, magneticstriction, etc. motors; shape-memory alloys SMA build-ups, etc.). The instrumental interposition grants acknowledged benefits: on-progress monitoring, easy local navigation, position/force accuracy, tremor filtering, pre-set planning, remote operation, etc.. The series of interventions already carried with robotic aids is quite large, covering simple implants and, step by step, moving toward higher sophistication duties.

This survey of established technologies and acknowledged solutions shows the growing interest of medical robotics and, specifically, the actual relevance of surgical equipment. Aiming at minimal invasiveness, robotic tools will be highly miniaturized and need to include every required capability into autonomous units.

### 3.1 Robotic intracorporeal equipment

An individual device may be a specialized sub-assembly of more complex robotic equipment. Active intracorporeal devices deserve the highest level of attention, as the MEMS technology is probably the best way to deliver enhanced performance function-
Robotic surgery: noteworthy devices

oriented aids, consistent with the requirements of minimal invasiveness. It is worth distinguishing these devices as application devices and interaction devices. The former consist of probes (inspection, drug-release, etc.) and effectors (dissection, legation knitting, etc.); these aids range from simple fixtures (catheters, endoscopes, travelling pills, etc.), to highly sophisticated systems for remote surgery. Insertion can be performed through natural ducts or incisions; in this case, the classification mainly deals with: externally manipulated probes, intracorporeal travelling worms and navigating intelligent pills. Because of miniature video-cameras, endoscopy becomes a widely applicable technique with minimal modification for capturing details and enhanced versatility (for mobility, magnification, restitution, etc.). The family of externally manipulated probes encompasses other areas to deal with specialized instrumental aids covering other tasks and, gradually, acquiring autonomy for path tracking (worms, etc.), or for navigation (intelligent pills, etc.).

3.1.1 – Active catheters

Considerable resources have been invested in the design of active catheters. Most of these miniature tools are actuated by shape memory alloys, SMA (Anthierens00). This kind of catheter is able to adapt its shape to allow smooth entrance and progression into the body. In Japan there is a great deal of active research on miniature polyarticulated fixtures. Different innovative catheters and endoscopes have been designed and successfully tested. For each apparatus, several improved releases exist and some examples are covered below: Prof. Esashi, from Tohoku University (Tohuku04), has developed a number of different catheters; an example miniaturized apparatus (1.2 mm diameter) is shown in Fig. 3.1. The modular lay-out exploits a sequence of segments, each actuated by three SMA linear actuators, placed 120° apart (Park99). The circuits that drive the actuators are embedded in each segment; three common lead wires, along the instrument, provide the communication. The switch for the SMA actuator is obtained by an high current MOS transistor. Standard CMOS technology is used to develop the circuits. The Olympus Optical Co. is a leading supplier of surgical endoscopes (Olympus04b). The company owns a portfolio of hundreds of patents (e.g.,
patents US4930494 and US4884557, Espacenet04). Slightly different from the Esashi catheter, the tube type manipulator is a shape memory alloys (SMA) poly-articulated device (Fig. 3.2a), having, at the distal point, a mean position accuracy of ±0.5 mm, for a maximum load of 1.5 g (dimensions: 40 mm long, 0.5 mm wide and 150 mm thick). A series of twin SMA plates (one divided into 2, one into 3 sectors) provide the tool actuation. The in direct heating of the SMA plates causes control problems, and, as for all SMA actuated devices, the response time depends on the cooling speed.

![SMA coil](image1)

Working channel (Φ 0.3 mm)

![SMA coil](image2)

A special thin film Multiple Function Integrated Film, MIF, was developed which embeds heater, sensor and actuation functions and model-based linearization was implemented to describe the SMA hysteresis (Aramaki95). Another SMA actuator from Olympus is the extra-slim active bending catheter (outer diameter 1.5 mm, inner diameter 0.6 mm). The apparatus is equipped with light/vision device and contact sensors (Fig. 3.2b). Three SMA wires, running along the tip, provide the bending force. If a sensor detects a compliant wall, the bending tip bends to avoid further contact (Howe02, Yamakawa02).

3.1.2 – Endoscopes

Endoscopes are basically used for examining the interior of a body organ. Referring to the access into the body, the endoscopes can be non- or minimally-invasive; for example colonoscopy is a non-invasive procedure, while arthroscopy is minimally-invasive.
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(Asari99). The endoscopes directly move from the catheter concept or classic endoscopes (more or less flexible pipes, driven by the surgeon from outside the body), and lead to classes of new devices, such as worms and pills. Worms are small rovers, generally devoted to the exploration of the digestive system, able to navigate autonomously inside the body. Usually wires, pipes or cables provide power and signals to them. Pills are rovers with no physical link to the external environment. Navigation strategies require further development and also the actual size remains a problem. Shape-memory alloys (SMA) locomotion is a common technique in several developments aiming at worm-like walking. With conventional endoscopes the preoperative scans provide a series of images which are parallel slices of the body zone to be treated. Grey scale photos are interpreted by the surgeon or are processed by a workstation and transformed into 3D models. The data provided by the scan is often fuzzy for at least two reasons: - because of bones overlapping or in the presence of deep cartilage, the resulting scan image is not sharp. Moreover, the density and orientation of the images from the scan is usually constant over the scan zone, so it is not possible to have easy access to the relevant details. Due to this lack of information, the surgeon is only able to obtain a precise idea of the real condition of the patient during the procedure.

A conventional endoscope (Fig. 3.3) is made up of a flexible pipe with a head, carrying a camera, oriented by acting on knurls, when manually inserted into the body. Four cables are connected to the head and the surgeon by means of knurls can orient the endoscope tip. The endoscope developed by Hirose exploits springs and wire actuation (Fig. 3.4a). Setting the wire pull causes bending (Hirose93). The architecture can equally be brought about by SMA springs (Fig. 3.4b). To achieve quick responses, Ikuta uses a fluid cooling circuit (Ikuta88, Otsuka02).
The active endoscope proposed by Honda Seiki KK (patent JP2000175865, Espacenet04), is actuated by magnetic torque (Fig. 3.5a). Along the body of the endoscope are fastened one or more ferromagnetic cylinders, the tip of the instrument carries the end effector. To increase flexibility, the magnets are connected each over by compliant spacers. The control of the endoscope is achieved by a magnetic field around the instrument, varying its intensity and direction. The solution is easy to manufacture, cheap and allows to highly reduce the diameter of the instrument.

Honda Seiki KK developed a second active endoscope (Fig. 3.5b), using shape memory coils (part 1) to bend the endoscope along a 3D path. A driving module (part A) enables forward and backward motion (patent JP2000070269, Espacenet04). A pressure sensor (part 2) is positioned on the tip of the device, as feedback for the real time control. The surgeon remotely controls the device using a finger manipulation unit (part B). A magnetic sensor gives real time information on the tool actual shape. The data flow is supervised and ruled by a CPU.

Olympus Optical Co. Ltd. is one of the world leader suppliers of endoscopes. The company designed several innovative active endoscopes. The here described example is composed by a sequence of identical modules (Fig. 3.5c).
Robotic surgery: noteworthy devices

Figure 3.5 – a) Magnetic Honda endoscope. - b) Pressure sensor. - c) Olympus endoscope

Two different kind of modules, both actuated by SMA, are reported (part A and B). Module A carries two flanges, each other opposite with given spacing, and connected by a restorable and flexible joint (part 1). SMA wires are spread along the joint: these are contracted by heating, due to shape memory effect, assuring large bends (patent JP3139325, Espacenet04). Two shape memory alloy coils are placed, symmetrically with respect to an axis, between the flanges of module B and memorise a close-winding loop (patent US4930494, Espacenet04). As for module A, the SMA is heated by electric current; the bend angle is proportional to the amount of current supplied to the two coils. A sensor detects the actual bend angle of each segment. The endoscope is inserted, for example, along a cavity: only the target angular position of the leading segment is chosen, the detected bend angle of each segment adapts to the target angle for each subsequent segment. The control of these redundant endoscopes is generally difficult; fuzzy reasoning, based on the difference between desired and measured values, enables the endoscope to be inserted smoothly (patent JP3085132, Espacenet04). The endoscope formed by a series of modules B is now an industrial reality, Olympus commercializes this varying stiffness device with the name EXERA Innoflex™ (Accuray04); the surgeon, during the insertion phase, needs to apply on the instrument a smaller thrust, consequently the patient comfort is increased.

Usually the temperature of SMA is raised by electric current; Computer Motion Inc. has
looked after an endoscope (Fig. 3.6), actuated by SMA elements heated by fluids (patent US5645520, Espacenet04). Each module of the endoscope is formed by an inner SMA rod (part 1) and an outer elastic pipe (part 2): the fluid flows through channels adjacent to the SMA element. The shape changes, by varying the temperature of the fluid (part B).

![Figure 3.6 – Pipe endoscope](image)

The Stanford University has studied several SMA active joints for endoscope actuation (patent US5556370, Espacenet04). The Ti Ni wires are coiled around the body of opposing joint halves (Fig. 3.7); joints size is compact, angular motion is large and heat dissipation is limited. The joints, having limited twist stiffness, are compliant and minimize invasive trauma.

![Figure 3.7 – Endoscopic joints](image)
NG Wan Sing has conceived an autonomous pipe-robot to perform endoscopic procedures in tubular organs (patent US6162171, Espacenet04). The segments, connected by flexible articulated joints (Fig. 3.8) are powered by pneumatic actuators (part A). The flexible linear actuators, like the feet of a centipede, push against the walls of the organs; the direction of each actuation can be flipped to allow backward motion (part B). A camera is placed at the distal end of the robotic endoscope. A central cavity running along the endoscope houses: electrical wires for the camera imaging, an instrumentation channel and a network of tributary channels for the distribution of pressure to the linear actuators.

CEDAR-SINAI Medical Center and the California Institute of Technology propose a robotic endoscope (Fig. 3.9) propelled by gas (patent US5662587, Espacenet04). The device, composed by a series of modules, can be used to accomplish both humans and animals endoscopic tests. Different kinds of modules have been designed, e.g., traction modules (part A and B), bending and extending modules, etc. A gas line provides compressed gas for lumen insufflation and actuation. The endoscope is able to bend and advances using either inchworm-like or snake-like locomotion. Example lead modules are: cameras, ultrasound transducers, drug delivery modules, therapeutic devices and surgical tools.
The arthroscope of the Santa Anna laboratory in Pisa, Italy (Fig. 3.10a), is designed to provide further data on the local area of the operation. The data fusion resulting from the general 3D models (from image scan) and the zoom details (from the arthroscope), provide valuable knowledge that helps the surgeon to drive the arthroscopic instrument along an accurate path and to keep the desired tool position and attitude in respect to the anatomical structures (Dario00). A commercial optical localizer tracks the absolute position of the apparatus with three cameras placed at the surgical scene. The cameras detect IR pulses, emitted by LEDs mounted close to the arthroscope handle, and the unit computes by means of geometrical triangulation, the coordinates of the tracked objects (Dario00). The multi-joint mechanical structure is cable-actuated (Fig. 3.10b). A position sensor measures the tip attitude and a force sensor detects the contact with delicate tissues in the knee (Fig. 3.10c); the overall error is 2.3 mm.
Robotic surgery: noteworthy devices

The Laboratorie de Robotique de Paris, LRP, is active in the field of robotic surgery. Innovative endoscopes, surgical tools and haptic devices are currently under development. The worm-like endoscope (Fig. 3.11a) is formed by a sequence of segments articulated to each other by pin joints (patent WO02096276, Espacenet04). Each link is mounted 90° apart to the previous one (Fig. 3.11b), to allow 3D motion (Chapelle02, Kuhl02). The segment actuation is performed by the opposing movement of two SMA springs. An integrated circuit is located on each segment for the control. The elongation of each spring is determined by electric heating; the desired spring length is measured by miniature sensors and controlled by pulse-width modulation of the electric power supply (Chapelle02, Kuhl02). Pressure sensors cover the apparatus’s external surface. A network, running along the endoscope, transfers the data to a computer located in the operating theatre.

Figure 3.11 – LRP intestinal endoscope

The outer diameter is 8 mm but the length is theoretically unlimited. The device is specially designed to explore the intestine with a camera. The LRP has developed several control algorithms to facilitate the endoscope’s insertion (Fig. 3.11c). The endoscope invented by Dr. Gründler, a Swiss surgeon, consists of a multiplicity of aligned segments, connected to one another by joints (Fig. 3.12). An electronically
controllable actuator is assigned to each joint; the actuators are bellows subjected to a controllable pressure, for example, by heating an easily evaporable liquid contained therein. The information about the angular positions of each segment passes through the joints, one after the other, in the direction opposite to the direction of the endoscope’s advance. The joints can be built as hollow spherical sections, which can be snapped together (patent DE3707787, Espacenet04).

The Electrostrictive Polymer Artificial Muscle, EPAM, is a promising new actuator with high (up to 30%) specific strain energy and short time delays (as compared to SMA) response. The Stanford Research Institute, SRI International (California, USA), has designed a snake using EPAM (Fig. 3.13a), made up from several modules, linked by an inner spine (Kornbluh98). Three EPAM linear actuators, placed 120° apart to yield bends and twists, power each module. The snake is suitable for use as an endoscope. Pennsylvania State University has also designed another EPAM snake-like endoscope for low invasive tasks (Frecker03). Three layers form the segmented actuator; a central passive substrate sandwiched by two layers of EPAM (Fig. 3.13b). Each EPAM layer consists of a number of active material slices; every slice having two electrodes independently wired. Each segment has an upper and a lower active substrate. Since the
copolymers expand upon application of an electric field, only one layer of each segment can be actuated at a time. The voltage level is used to control the magnitude of curvature; the Pennsylvania State University has developed an analytical model to predict the free deflection and blocking force of such segmented actuators.

The Imperial College of London has designed a class of endoscopes specially designed for neurosurgery; this kind of operation requires high accuracy. First the surgeon analyses the preoperative MR images of the patient’s brain to locate the site to be treated. The patient wears a stereo-tactic frame on his head (Fig. 3.14c); on this structure a parallel architecture, derived from the Stewart platform, is secured which carries the endoscope (Fig. 3.14b). The 3-degrees of freedom hand held tool, equipped with force feedback, helps in inserting a needle to the depth of the abnormality (Fig. 3.14a). High accuracy is required to reach tumours and haematomas; the parallel kinematics provides a spatial resolution of $25 \mu m$ (Starkie98). Neurosurgery can also be performed by different approaches; e.g., recently experiments involving miniature robots, inserted through a small puncture in the skull and guided to the brain, through 1.5 mm diameter blood vessels, have been developed.

(a) Endoscope DoF  (b) Force feedback  (c) Surgery tool prototype

Figure 3.14 – Neuro-endoscopic operating instruments
EndoAssist, from Armstrong Healthcare Limited (Fig. 3.15), is a robotic arm that holds the laparoscopic camera during surgical operations (Armstrong04). The robot, similarly to Pathfinder™ (Fig. 3.46c), is wheeled. The movements of the surgeon’s head, tracked by an infrared sensor linked to a headband, drive the camera. The control is intuitive, the camera is automatically oriented in the direction where the surgeon looks; the device is able to save over 10% of the operation time. Whenever necessary, the robot can be remotely controlled by a joystick, via a modem link. The wheels allow easy displacement; the tip carrying the camera is detachable for autoclaving. The robot, already used in thousands of interventions all around the globe, provides steady images avoiding the problem of hand tremor.

Extended and enhanced operative capabilities, together with cost and size figures, distinguish the Grenoble University laparoscope (Berkelman03). In reality the task range expands to cover functions of more complex robotic set-ups reviewed in the next section, but the apparatus is so small as to be directly secured to the patient’s body. Three electric motors drive the endoscope: two control the instrument rotation and inclination (Fig. 3.16) and the third leads, by cable, tool insertion, though the trocar, into
the body. A compression spring ensures the instrument’s exit. A similar configuration is under study for carrying surgical instruments, such as grippers and scissors. It will be necessary to add to the structure an additional degree of freedom (DoF), to control the end effector’s action.

![Endoscope design](image1)

![Endoscope prototype](image2)

(a) Endoscope design  
(b) Endoscope prototype

*Figure 3.16 – Grenoble laparotomic endoscope*

### 3.1.3 – Autonomous worms

Several kinds of miniature robots able to walk inside rigid pipes have already been created. For example, the pneumatic robot from Kato (96 mm long and having a diameter of 18 mm), is able to move inside tubes, using the stick and slip strategy, at a speed of 77 mm/s (Kato98). When the pipes are made of deformable tissue (i.e. intestine), the difficulty increases. Mobility is the preliminary challenge and then, the autonomous accomplishment of assigned tasks can develop. The Santa Anna University of Pisa has worked for several years on the development of a walking worm for colonoscopy (Fig. 3.17b). The problem of the inchworm motion was solved using a
combination of different strategies; each new improvement has been tested to verify its efficiency. The device (90 mm long, 18 mm diameter) has three locomotion modes: inchworm, sliding clammers and colon inflating (Dario02). The first resort to combined actuation, through a clamp, sticking at the wall and an extensor, providing positive extensions. The second uses tendon stretching and two pairs of clamps. The most successful worm, equipped with two clamps, exploits sucking air where the worm has to go and pumping when it has passed (Fig. 3.17a). Each time, clamping is obtained by tissue-sucking (patent EP0838200, Espacenet04) and jaw-pinching. The 45° rotation is achieved with 11 mNm torque supplied by 3 small SMA springs with a 120° layout; the cooling is achieved by air re-circulation.

The Katholieke Uneversiteit Leuven was involved in the design of one of the first intestine-walking robots. The rover (95 mm long, with 15 mm diameter) adopts a classic inchworm procedure for the motion. The colonoscope moves forward like a mountaineer by alternative grasps and body extensions. On both extremities, two locking modules are located, while the extensible part is located at the rover centre (Fig. 3.18a). The orientation is obtained by means of two bending modules (Fig. 3.18b),
formed by a stack of links (Fig. 3.18c), each actuated by SMA (Reynaerts96, Peirs97, Peirs00). The layout follows binary mode control; each link includes a selection circuit, to enable one or more DoF, by means of commands transmitted by modulation of the power supply. The SMA actuation provides a simple means to create a sequence of grasp or extension states. The Katholieke Unversiteit Leuven and the Laboratorie de Robotique de Paris were actively involved in the MUSYC, MUltifuncional minirobot SYstem for endosCopy, project, with partners from Italy, Belgium, France, Germany and U.K., and Prof. Paolo Dario, from S. Anna University (Pisa), project coordinator (MUSYC Project 1997).

Despite the development of intestinal exploration by autonomous worms which is already a challenging task, the Katholieke Unversiteit Leuven decided to perform a further step. Why not directly accomplished minimally invasive robotic surgery from inside the body? To achieve this dream, the new generation of tools will be equipped with two or more miniature mini-arms, able to drive cameras and surgical instruments (Peirs97). Two mini-arms have been designed: - a 5 mm diameter SMA actuated stack of links (Fig. 3.19a); - a 14.4 mm diameter 2 DoF mini-arm powered by electric motors (Fig. 3.19b). Referring to the latter solution, the distance from the end of the front
clamp to the tip of the camera is 40 mm.

(a) SMA mini-arm

(b) Motorised mini-arm

Figure 3.19 – Leuven intestinal worm mini-arms

The Korea Institute of Science and Technology has designed a rover (Fig. 20) that moves forward and backwards using a set of miniature wheels. Each of the wheels is normally in contact with the inner wall of the intestine. The rotational force is transmitted to the wheels, for instance, by a driving shaft and a coupling (patent US2002173700, Espacenet04). In the impulsive worm, from the Korea Institute of Science and Technology, some flexible supports are placed around the rover, to keep the friction between the rover and the colon wall low (Fig. 21). A pneumatic impulsive actuator propels the apparatus (Young01). Four parallel linear actuators allow steering. The camera is placed on the worm’s head and an LED illuminates the scene. A shock absorber protects both camera and LED from impacts (US2002111535, Espacenet04). The impulsive propeller transfers the momentum to the worm. Two kinds of propellers have been designed and tested; pneumatic reactive actuators and pneumatic impact actuators. A piston, sliding inside a chamber, forms the reactive actuator. The piston is
pushed by air (pressure 50 kPa), coming from outside of the body; a spring is placed to contrast this force. The pneumatic actuator and the spring work in opposition and depending on which is larger, forward or backward motion is obtained. The variation of these two opposite forces, and then the rover direction and velocity, can be varied with the input signal of the solenoid valve that controls the air flow into the actuator. The impact actuator has no spring; once the piston, due to the air push, impacts on the chamber wall, vacuum suction is employed to return the piston to its initial state. A second impact, opposite to the first one, is then generated. Both the actuators provide propulsion by cyclic impulsive pushes; the on/off time of the solenoid valve of the air inlet can be, for example, 45 milliseconds.

The locomotion of the following apparatus is inspired by nature (Byungkyu03). Like a centipede, several legs cooperate to provide locomotion (Fig. 3.22a). Each leg tip describes a periodic ellipsoid motion and the phase difference between the adjacent legs generates a wavelike tip movement. The phase difference between the legs is an important parameter for the insect’s displacement. The worm is equipped with two sets

![Figure 3.20 – Korea worm](image1) ![Figure 3.21 – Korea impulsive worm](image2)
of legs, respectively disposed along the upper and lower part of the body. The link mechanism that moves each foot, is now described (Fig. 3.22b). An electric motor, with a 1/264 gearbox rotates the central worm shaft which then rotates the gears in each leg. A crank, fixed to the gear axis, describes a circular trajectory. There is a slot along the lower part of each leg. The leg top, linked to the crank, describes a circular trajectory, while the slot slides along a pivot pin fixed to the centipede frame. By backward motor rotation, the rover inverts the direction of motion. It is possible to steer the robot by connecting at least two locomotive modules with parallel linear actuators. The 40 mm diameter rover is 125 mm long and can apply a maximum driving force of about 1 N. The wave motion of the legs provides a smooth motion, without damaging the wall of the colon; the velocity inside a pig colon is about 1 mm/s.

![Figure 3.22 – Korea centipede worm](image)

### 3.1.4 – Navigating pills

Non invasive surgery represents the next step (Clayman01). The intelligent pill, currently under study in different laboratories all over the world, when swallowed, collects data concerning the patient’s health, makes analyses and diagnoses then releases appropriate drugs to treat the condition.
Once the functions of end-effectors and of carrying mini-arms are distinguished, one clearly acknowledges that the latter does not provide direct intervention and, in any case, can leave-out relevant side effects. Our survey shall not omit tomorrow options of robotics. In the last years, several companies and Universities aimed at designing miniature pills able to explore the gastrointestinal tract. The RF System laboratory in Japan (Norika04a) has created the Norika3 pill, able to monitor the intestine with a small camera (Fig. 3.23a). The miniature capsule contains the optics and the electronics (size: diameter 9 mm and length 23 mm). Two LEDs, located inside the pill (Fig. 3.23b), light the digestive walls. The camera is on a flexible mount and the surgeon, from outside, by means of a joystick, can control the camera’s orientation. The power source for the pill is provided by external magnetic fields, generated by a garment worn by the patient which electromagnetically couple to a coil in the pill (Norika04b). The pill gives 30 images per second by radio signals. The capsule, for safety, has no battery, and costs about 100 US dollars. At the Norika3 homepage (Norika04b), a video illustrates the pill’s working principle.

The Norika3 pill is designed to explore the intestine; additionally scaling a similar device
will allow exploration of the veins. Leslie Rubinstein, from Renaissance Technologies, USA, aims at a capsule, in the millimetre range, able to navigate inside the blood stream, and to locate and destroy tumours (Rubinstein00). The propulsion is provided by the William McLellan electric motor (size of 0.397 mm$^3$), through vibrating cilia (similar to those of paramecium). Cancerous cells are obliterated using a high-powered laser diode to vaporize the unwanted tissues. Samples of the blood plasma can be tested inside a closed chamber, with the ability to do chemical analyses.

CRIM laboratory from the University of Pisa (CRIM04), proposes a walking pill with a front eye (Fig. 3.24a). Like a space ship, the pill is initially covered by a coating, when the capsule enters in the stomach, the acids cause the coating dissolution. This kind of coating is, eventually, used in pharmaceutical applications: the speed of coating dissolution can be chosen varying its thickness and material. The length of the pill is about 30 mm, its diameter is from 13 mm to 35 mm with fully deployed legs.

Prof. Brad Nelson, from the ETH IRIS, is designing a micro magnetic robot for biomedical applications (ETH02). The miniature submarine, 800 $\mu$m long and 50 $\mu$m thick, is small enough to explore veins (Fig. 3.24b). The frame is made of ferromagnetic material. Once the device is injected into the patient body, the position and orientation of the submarine can be chosen varying intensity and orientation of an external magnetic field. The first prototype has been already built and tested. Blood speed varies from 0,05 to 0,7 m/s: magnetic forces are sufficient to win the blood steam. Soft magnetic materials generate high fields, with drawback to be only temporary, and the hysteresis effect has to be taken in account. Permanent magnetic materials are better controlled. Future research aims at integrating in the submarine proper components, like: cameras, sensors and pumps.
According to the prospected ideas, it is interesting to create a device able to "seek and destroy" tumours, without damaging the close regions (Martin01). Professor Ferrari, from the Ohio State University in Columbus, intends to achieve this result by a fleet of miniature agents (Ferrari01); two solutions are sought: miniature particulates are injected directly into the bloodstream; larger submicroscopic devices enter in the body orally or by inhalation. The molecules, covering the outer surfaces of the particles, have lock-and-key binding specificity with molecules that support the growing cancer mass. Once the particles dock, a compound is released that forms a pore on the cells membrane; the cell cannot gather nutrition any more, consequently the cell, the blood vessel and the cancer mass die. The idea provides submicroscopic implantable drug delivery agents (Fig. 3.24c): a membrane protects therapeutic substances from attack by the body's immune system. Today, Ohio State University is able to manufacture 1 μm size particulates and can produce, by etching, nanoscale pores with 6 nm diameter.

Figure 3.24 – a) Legged-pill - b) Micro-magnetic robot. - c) Drug-delivery agent

3.2 – Remote-surgery environments

Surgery is moving from conventional open theatres to endoscopic intracorporeal procedures, aiming towards non-invasive operations by micro-robots located without any incision through natural orifices or blood vessels (Clayman01). More usually
laparoscopic surgery is performed through trocars, properly inserted and anchored. Several minimally invasive surgical instruments, held and driven by hand, are available. For example, the working principle of the Articulator Instrument, from Imagyn, is shown by an interactive animation (Imagyn04). Today various robotics systems exist that can be operated remotely (Nagy03). Some commercial systems are compared in figure 3.25.

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*Figure 3.25 – Robotic surgical systems*
A detailed and wider classification is found in the recent paper by Taylor (Taylor03). Three remote-operated robotic set-ups are available: Masor, RAMS and da Vinci®. The basic functions are integrated to combine monitoring and actuation capability, within a single stem that is designed specifically for the tasks to be accomplished. Remote surgery today is distinguished from the traditional approach, mainly by two factors:

- the information system collects the monitored data to provide a visual reconstitution of the surgical theatre;
- the robotic instrumental aids undertake the surgical procedure without direct in situ human manipulation.

Together, these two factors enable the development of complex surgical systems, whose sophistication expands depending on the required functions. The present survey is principally interested in the instrumental aids necessary to replace the surgeons’ manipulative capabilities. The three remote-operated set-ups (Masor, RAMS and da Vinci®), address different issues, from specialized duties to general purposes. Their philosophy, accordingly modifies, and provides clues to the future development of even more sophisticated equipment.

### 3.2.1 – Orthopedic surgery

Several example implementations are common practice, in the different surgery areas. As for orthopedic surgery, for instance, during the total knee replacement procedure damaged surfaces of knee bones, robots can fully place prosthetic implants. Knee bones are cut to host the prosthesis; only if the surfaces match exactly and the bone axis is preserved well aligned the implant works properly and lasts long. The task of robots, like Caspar, URS, Robodoc and Acrobot, is to increase the accuracy of orthopaedic interventions (Fig. 3.26). The design of Acrobot, from the Imperial College of London,
is focused on safety; the architecture, the recording procedure and the control are all studied to be intrinsically "safe" (Jakopec03). To keep the motor power low, the surgical platform is formed by two components; while the small spherical manipulator (Acrobot) is cutting, the heavy gross positioning device is frozen. To limit damages in case of error, the Acrobot architecture limits mechanically the workspace. Acrobot has 4 DOF; 3 DOF provide jaw, pitch and extension, 1 DOF powers the cutting tool. To cope with an accidental leg displacement during the operation, the tip of the cutter is used as a probe; the sampled points are real-time compared with the preoperative data. Control safety is enhanced, by coupling two encoders for each motor of the gross positioning device. The surgeon controls by hand the robot, driving an handle located close to the cutting head; the robot suggests the target area increasing its stiffness when the tool approaches the boundary of the safe area.

The Israel Institute of Technology has developed Masor, a miniature medical robot (Fig. 3.27). Masor is the final result of the MiniAture Robot for Surgery (MARS) development. The robot has the task of assisting surgeons in precisely guiding handheld surgical tools in line with a computerized, image-based, pre-operative plan along given
trajectories (Shoham03). The apparatus is compact and can be directly attached to the bone on which the operation is being performed. The parallel structure provides high accuracy and precision. Masor is only a partially remote surgery system; while the robotic control, and hence the instrument positioning, is performed remotely, instrument movement is locally steered by the surgeon.

### 3.2.2 – Eye surgery

The Robot Assisted Micro Surgery (RAMS) system originates from collaboration between the NASA Jet Propulsion Lab. and Micro Dexterity Systems Inc. (MDS). RAMS will enable surgeons to perform operations on the brain, eye, ear, nose, throat, face and hand (Charles97). The 6 DoF slave mini-arm is compact and lightweight. The mini-arm is 25 mm in diameter and 250 mm long. The 6 DoF master has the same diameter as the slave and is 10 mm shorter (Fig. 3.28).

![Figure 3.27 – Masor system](image)

![Figure 3.28 – The RAMS system](image)

The movement is enabled by motor driven cables. The master is able to measure applied hand motions down to a relative positional resolution of 25 \( \mu \text{m} \) and the slave robot can read its tip position with a resolution of 1 \( \mu \text{m} \). RAMS control mode includes task-frame referenced manual force feedback and textural feedback. The system has been evaluated...
in actual clinical procedures and is supplied through a cooperative NASA-Industry venture with MDS.

### 3.2.3 – Endo-urology surgery

The robot handling effectiveness is directly exploited to control the attitude and position of end-effectors directly operating on the patient. Endo-urology presents very effective devices. Percutaneous renal access is conservative surgery procedure, suitable for intra-renal calculi removal. The stones, first, are reached by a percutaneous tract, then broken and removed from the patient body. The percutaneous tract is created by a sequence of steps: initially a vision system is used to safely insert the needle; the tract is, then, progressively dilated replacing the needle each time with slightly bigger catheter. Needle insertion and placement are delicate tasks; wrong insertions cause post-operative pain and can produce haemorrhage. Imperial College of London and Johns Hopkins University propose surgery robotic systems with the aim to automate, facilitate and improve the accuracy of the procedure.

The range of procedures typically performed by an urological department is relatively wide; for reasons of cost, Imperial College of London is trying to design a unique 'generic' urological robot, onto which task specific intelligent tools may be attached. The English robotic system has 5 passive encoded DOF (Fig. 3.29a); the needle is driven by hand by the surgeon. Once the suitable position is reached, it is frozen by electromagnetic brakes. Control is obtained by ultrasound images (Imperial04). The robot performance has been evaluated in laboratory: the robot has successfully accomplished brachy-therapy and biopsy procedures. The device, by means of a needle, is able to deposit a series of small radioactive seeds within the prostate through the perineum, accuracy is less than 1.5 mm (Challacombe04).
Professor Dan Stoianovici, from the Johns Hopkins University, has designed, built and tested RCM and PAKY (Fig. 3.29b). The surgery system is able to perform fully automated placements in soft tissues. RCM is a general porpoise Remote Centre of Motion module for robotic procedures, PAKY is a needle driver module for the Percutaneous Access to the Kidney (Su02). RCM presents a compact and light design. The fulcrum point is located distal to the mechanism itself; the needle can translate and rotate preserving constant the position of its insertion point. The system has overall 10 DOF: 7 passive DOF are used to orientate and position the arm that sustains RCM; RCM has 2 active rotational DOF for positioning the needle inside the patient, PAKY has 1 active DOF for driving the needle. The surgeon plans the needle insertion path, from bi-planar fluoroscopy images, then the robot accomplishes the needle displacement. By respect to traditional techniques, the robot is able to reduce tremor, to minimize radiation exposure and to increase accuracy; error is less than 1 mm. The needle, an inexpensive sterile disposable part, is radiolucent, to allow a real time control. An electrical bio-impedance sensor provides the needle force feedback.

AcuBot, from Johns Hopkins University, is an evolution of PAKY-RCM system. This 6 DOF robot will be traded by ImageGuide (Fig. 3.29c); the passive DOF mini-arm, carrying the needle, is driven by a Cartesian positioning stage (Stoianovici03). Several
percutaneous nephrolotitomies tests have been accomplished, to evaluate the performance of these devices. Today, human hand is faster, but less accurate and firm than robotic arm. Time and accuracy of robotic tele-operations are similar to locally-aided robotic interventions (Challacombe04).

### 3.2.4 – Laparotomy and thoracotomy

One of the most challenging telesurgery procedures is a coronary artery bypass graft. Beating heart compensation is another active field of research. Probably the most famous robotic system for intracorporeal surgery is the da Vinci® by Intuitive Surgical, Mountain View, California (Intuitive04). The device includes a master, a computer controller and three robotic arms (Fig. 3.30): one for the camera; and two (hand driven), carrying surgical tools (Govindarajan01, Soler03, Tang03). In a recent development, a fourth operating arm, can be added to the system; this option further enhances the dexterity and autonomy of the robot, reducing the need for assistants.

![Figure 3.30 – da Vinci® surgery system](image)

The surgeon, during the operation, places his head inside the console and sees the stereo-images from the endoscope. As a result, the surgeon feels completely immersed
in the operative field. On 21 October 2003, Olympus presented a new release of the da Vinci® 12 mm laparoscope; the tool, equipped with three separate optical channels allows both detailed 3D images as well as panoramic two-dimensional images (Intuitive04). The robot arms weigh more than 500 kg and access for the assistants is not easy and the surgeon cannot readily see the operating scene. The surgery platform (patent US2003083673, Espacenet04), adopts cable drives to actuate tools, the joints have ±90° span. The end effector provides overall 6 DoF inside the body (sweep, tilt, insertion for engaging and yaw, pitch, roll for handling) and 1 DoF for the tool motion. Movements appear inherently intuitive; the two joysticks handles of the master, have a shape similar to classic surgical instruments. The device offers visual magnification, movement scaling and tremor filtering. Interference between the robotic arms or between the arms and the body of the patient occasionally occur. After a few operations, due to the sterilization process, the characteristics of the cables deteriorate and so it is necessary to replace the tools. More than 160 da Vinci® robots exist. The price of the system is about $1.2 million; it is necessary to invest $100,000 a year in maintenance, the cost in disposable equipment per patient procedure is about $1,500. The main benefits are less patient pain and trauma. The post-operative hospital stay is usually shortened to a few days from up to 2 weeks, thus reducing the hospital costs. The lack of force and tactile feedback is a major drawback of remote surgery. The latency is also a great hurdle for tele-operations for example in the battlefield. Wide band communication channels are being sought to improve remote steering and to enable computer controlled sequences, with the assistant surgeon overseeing the procedure. On 7 September 2001, the first transatlantic remote surgery (New York, Strasbourg) was performed, using the ZEUS® robotic system, by Computer Motion,
Goleta, California (Computer Motion 2003); the time delay was kept as low as 200 milliseconds. In March 2003, Computer Motion was acquired by Intuitive Surgical. The availability of specialized tools shows the rising interest in the field.

Present trends aim, more and more, at integrated set-ups, embedding special purpose fixtures into multi-purpose systems. Endovia Medical Inc. proposes a surgical platform for laparoscopic operations, focusing on general, urologic and gynaecologic actions, to precisely manipulate catheter instruments deep inside the patient (EndoVia04). The Laprotek™ System includes an input device and a slave station, with the surgical equipment and controller (Fig. 3.31).

**Figure 3.31 – Laprotek™ System**

### 3.3 – Surgical end-effectors

Out of handling effectiveness, robot technology is specially relevant to conceive duty-driven end-effectors leading to new intervention opportunities, as compared with traditional human habits. The domain is quickly evolving, as nano-scale devices pop-up. Example options are shortly mentioned to show new reaches. With the trend towards integrated set-ups, the request “high versatility and efficiency end-effectors” becomes winning option. It is important to increase the dexterity of the effectors inside the body, keeping the design as compact as possible. The final goal is to provide the surgeon with
user friendly aids. They are usually instrumental fixtures of the host robots rather than stand-alone instruments. Further implements need to be devised, granting proper power supply and information autonomy. After the merger between Computer Motion and Intuitive Surgical, the ZEUS® surgical system (patent US6007550, Espacenet04), is no longer on sale. More than 50 surgical apparatus were available ranging from 3 to 5 mm in diameter including needle holders, scissors, dissectors, graspers, scalpels, stabilizers and mono-polar cautery devices (Fig. 3.32a). The miniature articulated instruments have embedded mechanisms that assure 2 DoF inside the body: pitch motion and tool actuation. Referring to Fig. 32b: “a” is the last DoF at the carrier, “b” is the first DoF of the miniature tool and “c” is the clamp actuation DoF. The “b” and “c” articulations are decoupled. The device (patent WO0059384, Espacenet04), is especially suitable for use in endoscopic coronary artery bypass grafting surgery.

The da Vinci® is equipped with a wide range of 8.5 mm diameter tools (Fig. 3.33), i.e.: forceps, needle drivers, scissors, scalpels and shears etc. (Fig. 3.33a). The da Vinci® surgery arm has 6 DoF plus 1 DoF for the tool actuation. As for the ZEUS® arrangement, the DoF “a” and “b” are respectively the last DoF at the carrier and the

Figure 3.32 – The ZEUS® surgery tools
first DoF of the miniature instrument (Fig. 3.33b). Each of the two fingers of the clamp is independently actuated ("c" and "d"). The rotation of the clamp is obtained when both the fingers have the same speed and sense of rotation; whereas, in the case of relative movement between the fingers, the clamp is open or closed (patent US2003100892, Espacenet04). An interactive animation shows the da Vinci Endowrist™ features (Intuitive04). Lately the classic 8.5 mm diameter tool set has been extended with a new family of 5 mm diameter instruments, especially suitable for paediatric surgery. Smaller arms need less workspace to operate, have less collision problems and allow better visibility of the organs (minor vision occlusion). The 5 mm da Vinci® tools were used, for the first time, on 12 August 2003 when a gallbladder operation was performed on a sixteen-year-old girl.

To improve the dexterity of the da Vinci® surgical system, Intuitive Surgical has designed a new end effector holder (Fig. 3.34). This provides pitch and yaw rotation with no singularities. The apparatus is composed of several vertebrae, stacked in series (Fig. 3.34a); each vertebra is shaped to rotate in pitch or in yaw with respect to the neighboring one. Actuation cables are used to drive the vertebrae and to control the
motion. In specific embodiments, some of the cables are distal cables that extend from the proximal, through one or more intermediate vertebrae, to the distal one, while the remaining cables are medial cables that extend from the proximal, to one or more intermediate vertebrae (Fig. 3.34b). The cables are actuated by a pivoting-plate cable-actuator. This mechanism might include a number of small radius holes or grooves for medial cables, and some large radius holes or grooves for distal cables. The holes or grooves restrain the medial cables to small motion ranges and the distal cables to larger ones. Thus, the medial cables to the medial vertebra move only a fraction of the distal cables reach to the distal vertebra, in order to achieve accurate control of the vertebrae (patent WO03001986, Espacenet04).

![Wrist design](image1)

![Wrist prototype](image2)

*Figure 3.34 – da Vinci® surgery tools*

The actuator base Laprotek™ System drives one or more articulated mini-arms, each composed by members mutually joined by rotational links; these are actuated by, at least a tendon (patent US6692485, Feb. 2004, Espacenet04). Some of the mini-arm effectors (Fig. 3.35) are flexible (patent EP1303228, Espacenet04). A set of interchangeable 7.5 mm tools like scissors, cautery and needle holders is available: the mechanical design of the miniature graspers is specially interesting (patent US6554844, Espacenet04). The
Laprotek™ System requires regulatory clearance and is not yet commercially available (July 2004).

Different kinds of tools have been developed in the Technical University of Lódz, Poland for surgical operations. The RobIn heart-robot (Fig. 3.36), exploits 5 string actuation effectors: 3 drivers grant angular orientation; one DoF supplies opening and closure of the jaws. The last improves manoeuvrability by redundancy, to avoid obstacles and to operate backwards (Podsędkowski02). Strings are placed in separate modules and if a string breaks, the operation continues by replacing the module. The bunch diameter is 10 mm; 15W DC electric motors and zero backlash gears provide power. For clarity reasons, on figure 3.36, only two axes of rotation are shown.
The Michigan State University College of Engineering proposes the Dexterous Articulated Linkage for Surgical Applications (DALSA), designed for minimally invasive surgery (patent US6309403, Espacenet04). Gears and gear links compose the 3 DoF tool; its shape is similar to a crocodile: the device rotates the surgical tip by gears and actuates the clamp by cable. Three segments form the spine; each allowing a 60° rotation for an overall 180° articulation (Minor02). The design (Fig. 3.37a, 3.37b), shows the axis of rotation of the 3 spine segments. The limited number of segments (only 3), allows less force magnification and hence easier control. The linkages are made of stainless steel. Vectran tendons, manufactured by Cortland Cable, are incorporated. DALSA is about 36 mm long, can pass through a 10 mm port, and is capable of applying forces in the range of 4.4 N. The mechanism was optimized for handling a sewing needle. The gear thickness has been optimized, to equally distribute stresses within the respective segments and maximise the overall load carrying capabilities. The tool is compact, while assuring good dexterity, high load capacity, and fine motion capability.

![Figure 3.37 – Michigan surgery gripper](image)

The Institute of Robotics and Mechatronics of the German Aerospace Center, DLR, designed a gripper to be used as end effectors for minimally invasive robotic surgery (Fig. 3.38). The tool has 3 DoF: 2 on the cardanic joint, and 1 for the gripper actuation.
The surgical tool, carried by a robotic arm, is inserted through a trocar into the body. The robotic arm, carrying the instrument, usually has 6 DoF: the 2 DoF of the cardanic joint compensates for 2 DoF loss due to the trocar constraint. This tool, allows full manipulation inside the body. The mechanical structure of the integrated force/torque sensor can stand forces up to ±30 N without plastic deformation; the sensor measures up to ±20 N force and ±200 Nmm torque, with 10 bits resolution. Generally, there is friction between the surgical arm and the trocar; the force sensor has to measure only the surgery handling forces and not these friction forces. For this reason, the sensor is placed close to the tool tip; during the operation, the sensor stays inside of the patient’s body. The 10 mm diameter gripper is suitable for bypass grafts and valve repair. Position, velocity and force control algorithms as well as heart beat compensation have been developed and tested (Ortmaier03). The DLR has built another instrumented tool: a surgery scalpel having an embedded force sensor.

(a) Gripper design
(b) Gripper prototype

Figure 3.38 – German surgery gripper

The cardiac surgery device, from the Warsaw University of Technology, has the task of driving the needle during heart operations (Fig. 3.39). The 8 mm diameter apparatus has 4 DoF: 3 drivers to orient and position the clamp using a snake like structure, the fourth
one opens and closes the clamp (Mianowski02, Podsędkowski02). The snake-like structure includes three segments; when a segment rotates, the ‘snake’ bends. Electric motors with gears are located inside the box shown in Fig. 3.39a; this apparatus is very lightweight and relatively cheap.

![Surgery tool and Tool tip](image)

*Figure 3.39 – Poland sewing effector*

The University of Paris VI and the University of Genova have designed a tool especially suitable for coronary artery bypass grafting (Sallé04a, Cepolina04e). An hand held (minimally invasive surgery) gripper is sensorised to record the trajectory of the sewing needle, and the forces applied by the surgeon during a real operation. From the experiment, it has been observed that the piercing force is about 0.5 N, the wire stretch is about 1 N and the clamp force is about 40 N; these results agree with previous literature (Dong-Soo98). The relatively low forces needed, suggest that it is possible to feed the end effectors by electric motors and SMA actuators, located directly inside the wrist. The proposed instrument, object of this thesis, is composed of a sequence of modules having one or two DoF; the modules, each equipped with absolute angular sensors, are joined by a common mechanical interface. A simulator, based on genetic algorithms, has the task to find out the module sequence that better mimics the
surgeon’s gestures. The multiobject algorithm computes the range of each candidate apparatus, using four independent criteria: ability to perform the gesture, instrument dexterity, maximum joint torque and minimal distance to organs. Four modules, respectively, with one, two, two and one DoF (Fig. 3.40), form the optimal miniature apparatus (77 mm long with a 10 mm diameter); a prototype is being built. The apparatus, having 5 DoF for the actuation and 1 DoF for the gripper, is carried by a 6 DoF main arm; because 2 DoF are lost due to the insertion through the trocar, the overall manipulator has 3 redundant DoF. This additional dexterity is used to improve manipulation, to avoid organs and to prevent the obscuring of the endoscopic view.

Engineers from Daimler Benz have designed a tactile sensor, suitable for minimally invasive surgery (Fig. 3.41a). The sensor presents 8 small pyramids (Fig. 3.41b) on the top of each, there is a thin silicon membrane (Flemming97). When a force is applied to the pyramid, the silicon is stressed and the stress is recorded by a piezo-resistive element. The spatial resolution of the sensor is 1 mm; its sensitivity is at least 1 mbar. The sensors can be heated up to $135^\circ$C without damage.
Endostich™, from Tyco Healthcare, is a minimally invasive hand driven tool, able to simplify current endoscopic suturing technique (Fig. 3.42). The tool can suture (AutoSuture04), using both absorbable (Polysorb™) and non-absorbable threads (Surgidek™, Surgilene™). The ENDO-STITCH™ needle is 9 mm long, 0.9 mm wide and sharp on both ends. The suture is attached to the middle of the needle: each end has a locking slot; the slots are secured by a sliding mechanism. The needle can be attached either to the left or to the right jaw; the 10 mm diameter device avoids the continuous regrasping of the needle during the suturing procedure.
example, the applications for “ENDO-GIA™ Universal” are: laparoscopic stomach transection, mesenteric takedown, small bowel transection, jejunojejunostomy and gastrojejunostomy. The end of staple line can be articulated or not. These instruments can be charged with 30, 45 and 60 mm reloads. Auto Suture has optimized the design of the staples and of the anvil bucket to perform reliable staples even in the case of relative deflection between anvil and cartridge.

New robotic techniques can be employed to enhance the performance of classic surgical instruments. A classic problem related to the minimally invasive surgery is the loss of force feedback. The relatively high friction generated between trocar and effectors makes difficult to feel the actually applied force. A small, reliable, fully integrated with the instrument and sterilizable sensor could solve this problem. Several research laboratories are developing the rig. The Laboratoire de Robotique de Paris proposes an original approach to the problem (Fig. 3.44); the miniature force sensor, close to the tip of the device, is replaced by a bigger one located outside of the patient body (part 1), between the trocar and the handle of the instrument (Zemiti04). The sensor measures forces and torques, applied by the surgeon. A servo-robotic mini-arm drives the instrument, keeping the exerted forces under a certain threshold. The device, directly
Robotic surgery: noteworthy devices

placed on the patient body, splits in two parts: a compact spherical mechanism moves the trocar (2 DoF), additional 2 DoF make the instrument rotate and translate along its axis. The compact and lightweight rig compensates and cancels out the trocar friction as well as the device weigh.

Motion-and-effort compensation is winning aid in every critical situations. Operations, such as retinal vein cannulation or arteriovenous sheathotomy, require high precision; e.g., tool tip accuracy for vitreoretinal operations approaches 10 μm. The CRIM laboratory of the University of Pisa and the Robotics Institute at Carnegie Mellon University are investigating an handheld instrument able to compensate the surgeon erroneous movements. The first prototype of Micron (Fig. 3.45), from Carnegie Mellon, is 210 mm long, has a 22 mm diameter and weights 170 g (Riviere03). The instrument tip (part 1), is mounted on a 3 DOF parallel architecture driven by piezoelectric stacks. The back of the device hosts accelerometers and gyroscopes; estimation of motion error due to tremor and myoclonic jerk is performed at 1 kHz sampling. The tool can reduce 34% (from 91 μm p-p to 60 μm p-p) the amplitude of the erroneous motion.
As a final example the apparatus conceived at the University of Genova, PMAR Lab. will be described. Recently considerable resources have been spent to design micro wrists with the aim of adding several DoF close to the end-effector to gain manipulability. What we have today is the almost 500 kg da Vinci® main arm carrying the less than 50 g plastic French sewing gripper. The examples of the Masor system and the Grenoble laparoscopic device have shown that it is possible to design compact autonomous apparatus. We propose to house the basic micro-wrist within a miniature polyarticulated arm (Cepolina03). The snake-like mini-arm, described in detail in the following chapters, is able to autonomously insert itself inside the body of the patient, without requiring any carrying robot. The mini-arm comprises a sequence of modules, with re-setting joints; the final shape is achieved by modifying the coupling of the actuated joints.
Four options were considered (Fig. 3.46a): - one DoF modules with a pin joint and a micro DC motor; - two DoF modules with universal joints actuated by micro DC motors; - two DoF modules with elastic joints, cable driven by outer motors; - two DoF modules, with spherical joints driven by tendons, tensioned by clutches and actuated by a flexible rotating shaft (Cepolina03). For example, the overall view of the spherical-joint snake is shown (Fig. 3.46b). The modules have a 10 mm outer diameter and the final apparatus exploits up to six modules. The elastic-joint solution offers basic, cheap and compact layouts, especially suitable for further miniaturization: a 0.28 mm diameter cable can support up to 460 N. A sort of “basket” hosts and drives the surgical snake (Fig. 3.46c). Depending on the procedure a longer or shorter part of the snake will come out from the basket. The design provides a useful degree of redundancy to the end effectors; the DoF of the sections leaving the basket follow the snake path: the greater the distance, the higher the number of organs to avoid, and the higher the number of required DoF. Special task-oriented end-effectors are considered, e.g. a syringe and a self operating sewing device, capable of operating with a single thread (Fig. 3.47).

(a) Syringe
(b) Sewing machine

*Figure 3.47 – Example end effectors*

These self-powered tools are designed following a task-oriented and not an anthropomorphic approach. For example, the needle of the sewing machine does not replicate the movement of the surgeon hands; rather it describes a spiral trajectory. The
project is covering the concept design, and the feasibility is assessed by virtual tests on digital mock-ups for current operative conditions. The different pieces of the modular lay-out are chosen from existing components and the test environments refer to data derived from similar missions. Future research will cover automatic exchange of surgical instruments.

### 3.4 – Surgical procedures

The previously mentioned devices are used as the end effectors of surgical robotic set-ups. These devices can be expected to develop dramatically in parallel with MEMS evolution and with advances in nano-technologies. One should principally focus on two requests: - the availability of task-optimized tools; - the capability of lower invasiveness in establishing the work-space. Up to now, anthropomorphism seems to have been the driving concept, replicating not only the surgeon’s hands and eyes but also his habits in reaching the operation points and in monitoring the progress of the operation. Most of the issues rely too much on these premises. Actually a one-to-one duplication is not currently possible. The operating theatre is different from the one used in open surgery and the tactile and haptic sensing are far from perfect. Remote surgery should be viewed as a guide to suggest new techniques suitably leading to programmed or to autonomous robotic devices, with higher reliability and effectiveness (indeed, during remote-steered operations, the time lost due to surgeon hesitancy cannot be avoided). Depending on robot versatility and task difficulty, alternative strategies can be determined and pre-programmed. For example, to execute a straight cut, the surgeon can select the start and the end point while the system provides comments on the plan. Once the action is selected the robot autonomously completes the task. Robot trajectories are smooth, have good accuracy, and are un-biased with no overshoot and no tremor and the robot
filters out the unwanted high-frequency motions of human operators. The surgeon, of course, continuously monitors the task in progress, and can at any time stop or modify or switch to a different plan. The new protocols differ from traditional ones, since the end effectors can be much smaller and the engagement paths can follow winding tracks, choosing safer routes. The presently available equipment already suggests the direction of expected changes. The operator will be seated during the whole procedure. In case of delicate tasks, such as suturing, the robot, besides tremor filtering, needs to execute the work according to the pre-set path, avoiding the surgeon’s macroscopic trajectory errors. With autonomy, some sub-tasks are given to robots and monitored with sensors. This is the case for complex tasks that are accomplished by strategies, interactively defined on multi-modal data. The da Vinci Navigator is software that enables the surgeon to follow the location of the tool tip on pre-operative images; the surgeon sees a ‘virtual operating theatre’ and checks whether the overall choice is correct. After the virtual procedure the surgeon evaluates the results. He can choose either to record the whole plan for on-line execution or to carry out a manual procedure to complete the operation. Indeed, virtual testing on digital mock-ups and life-cycle simulation are standard techniques in many technical areas, and the transfer to the surgical operating theatre is a straightforward accomplishment. The present review focused more on tools and fixtures, over which completely new procedures and protocols could be devised. The analysis, according to the task-specific suggestions, finally promotes a rather different approach, leaving out the carrying manipulator, and focusing on the end effectors, provided that the different functional requirements can be transferred to the frontend devices.

3.4.1 – Robot scanning and diagnoses assessment
The robot help in medical diagnostics, mainly, looks after exploiting the handling capability of dexterous arms, for the accurate positioning or the path-tracking of carried probes. These developments characterise by out-of-body handling devices, assuring high performance positioning and attitude control of the diagnostic head; the carried probe, out of the current imaging opportunities, could have in charge, as well, to localise high energy radiations for specific interventions.

The opportunity is specially useful in brain surgery. Stereotaxy is common technique used to achieve the high accuracy. Intracranial neoplasms, vascular malformations and epilepsy are examples of clinical applications. A 3D image of the patient brain is reconstructed by TAC or RMN, and the 3D map of the lesions is created. Once the record is completed, the surgical operation is performed under “augmented reality”. The surgeon is free to rotate and to translate the microscope in any direction, while a graphic workstation gives the real time laying of the sight plane, viewed from the microscope oculars, within to the brain 3D model (Giorgi00). The coordinates of the patient head and of the microscope are tracked and transferred in a common reference frame. Advanced stereotaxy navigation platforms, further, allow the real-time 3D representation of surgical instruments.

There are at least three ways to track the position of the microscope. It is possible to equip the microscope arm with encoders; in this case, even if the mass are balanced, the inertia lowers the motion fluidity. Some commercial microscopes adopt optical, ultrasonic or magnetic sensors positioned outside of the arm. Finally the arm can be equipped with encoders, motors and brakes. The slave robot arms follow accurately the surgeon movements.

Commercial neuro-navigation systems generally accept different data formats and offer
high spatial accuracy, enabling the surgeon to drive and correct the instruments trajectory (McInerney00). Surgiscope, from Elekta (Fig. 3.48), and MKM, from ZEISS (Fig. 3.49a), are two examples of robotic microscopes for frameless stereostatic procedures.

![Surgiscope](image)

*Figure 3.48 – Surgiscope*

Their control does not allow the autonomous execution of high level tasks, such as automatic calibration (Giorgi00).

Surgiscope is a parallel robot, placed on the ceiling of the surgical room; two cameras measure the position of LED located on the microscope and on the patient head (Elekta04). Zeiss-MKM can be, for example, employed for the implantation of epidural motor cortex stimulation devices (Pirotte01), lowering invasiveness (bone opening and skin wound); the robot hosts inside its arm the position sensors.

It is interesting to compare OPMI® Pentero™ (Zeiss04), the last born from Zeiss (Fig. 3.49b), with the MKM platform; Pentero™ design results lighter, less cumbersome and more ergonomic. Pentero™ is suitable for neuro and spine surgery; it offers integrated support for intra-operative angiography and fluorescence-based tumour resection.
PathFinder™ (Fig. 3.49c), is an existing image guided robot for stereostatic neurosurgery (Armstrong04). The images generated by CT and MR scanners, are processed from the annexed planning workstation. The recording process is automatic; the patient does not need to wear a stereostatic frame for scanning, it is not necessary to insert manually the scan co-ordinates. Records are performed via software. The robot maps the patient position by a camera; a dedicated software matches camera and scanner images, tools can be positioned with a sub-millimetre accuracy. The end effector can carry a range of motorised drivers for standard neurosurgical tools. The driving module moves the instruments along any chosen trajectory.

Robot scanning can be associated to remote interventions, accomplished by properly focused radiation. CyberKnife®, from Accuray, is a stereostatic radio-surgery system (Accuray04); the 6 DoF serial robot is equipped with 6 linear accelerometers (Fig. 3.50); a stereoscopic image system automatically detects and locates the areas to be treated. The technology avoids the need of rigid stereostatic frames, thus enhancing patient comfort.
3.5 – Training and pre-planning aids

Robot technologies are important not only as instrumental aids to broaden and to enhance human abilities for on-process interventions, rather, as well, as support method to modify and re-orient assessed habits and to help focusing on more-effective alternatives up-now disregarded since out of conventional human reach. To that purpose, resort to virtual-reality settings is particularly useful, and several special developments are available off-process for training purposes or on-process for planning and checking duties. Surgeons need several hours of training to become acquainted of minimally invasive surgery procedures. LAP Mentor™, from Simbionix (Fig. 3.51), is an example of virtual simulator. The whole intervention is accurately simulated by this platform: the surgeon can operate with two instruments inside the abdomen of a virtual patient (Simbionix04). A monitor offers a 3d realistic view of the scene; the organs are deformable and have natural colours. The handed instruments have force feedback, and a virtual instructor gives real-time advices.

Figure 3.50 – CyberKnife®
Figure 3.51 – LAP Mentor™

The integrated set-ups for robotic surgery, accordingly to the singled-out trends, assemble many functions, including real-time features (to expand surgeon abilities,
performance and effectiveness) and auxiliary options (to help planning the interventions and checking the effects). Both already apply, as general opportunities, independently from futures innovations provided by nano-technologies, as enabling support of robotics. Thus, even conventional surgery greatly benefit from extended robot functionalities.
Chapter 4

Actuation innovative technologies

The previous chapter has provided an overview about some of the surgery robotic aids actually used for surgical operations. In this chapter the actuators most suitable for micro actuation are recalled. The characteristics of each actuator are investigated and compared; power, size, weight, power source etc. Then, for each actuator, commercial catalogues has been searched. Because of the MEMS technology is new, to discover its potentiality, many laboratories create some demonstrators (Sandia04, Judy01); at the end of this chapter two examples of MEMS demonstrators are shortly described.

4.1 MEMS overview

The word MEMS, was officially adopted in 1989, in Salt Lake City, during the workshop in “Micro-Tele-Operated Robotics”; from that date, the number of companies that work in this field is each year constantly increasing. MEMS has been using the photo-chemical technology inherited from silicon manufacturing to create small size frames, sensors and actuators (Brushan04, Brooke04, Nanozine04, Maluf00). Depending on the size of the parts, its manufacturing tolerances are different (Fig. 4.1):
Actuation innovative technologies

The materials most often used in MEMS are: Silicon, silicon oxide, silicon nitride, ceramics, quartz, metals (nickel, gold, aluminum, copper), polymers, glasses. Manufacturing of small parts can be obtained using high precision CNC machining, micro-electro discharge machining, micro-injection molding, electro-deposition, Focused Ion Beam (FIB), deep UV lithography, micro stereo-lithography, wet etching silicon micro-machining etc. Assembly can be executed using Surface-Mount Technology (SMT). MEMS components are machined following this procedure: layers are deposited (Maluf00); photoresist is lithographically patterned, and then used as a mask to etch the underlying materials (Fig. 4.2). Lithography is a photographic process for printing images onto a layer of photosensitive polymer (photoresist) that is subsequently used as a protective mask against etching.

<table>
<thead>
<tr>
<th>Technology</th>
<th>For parts up to</th>
</tr>
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<tbody>
<tr>
<td>precision manufacturing</td>
<td>1 mm</td>
</tr>
<tr>
<td>silicon process and LIGA-process</td>
<td>1 μm</td>
</tr>
<tr>
<td>protein engineering</td>
<td>1 nm</td>
</tr>
</tbody>
</table>

*Figure 4.1 - Manufacturing tolerances*

*Figure 4.2 - Micromachining process flow*
The process repeats until completion of the microstructure. Despite the clean rooms and the machining tools used in MEMS are costly, the price of MEMS components is very competitive. Costs are scaled thanks to mass production in silicon array; during MEMS production, the image of the same component is mirrored and machined, on the same silicon wafer, hundred of times. Micro components sensors and actuators are compatible with the microelectronics in terms of size and in components costs. One of the critical points of the SMT is the integration of the interfaces used to provide power supply, information exchange, substance delivery. Ideally, a microrobot is a chip with integrated a microcontroller, sensors, A/D and D/A converters and actuators. Instrumental robot should be able to go into complex surroundings and locally repair defects, thus the machines would no longer have to be disassembled for repair. In a few years, microsystems will be able to perceive many events happening in their surroundings, to evaluate and then to convert the results into actions. Inexpensive mass production, a lower material content and low energy consumption will make the microproducts economically competitive.

### 4.1.1 – MEMS products

Some of the main areas of research of the SMT are: optical switching, mass data storage, inertia sensors (airbags), pressure sensors, fluid regulators, biochemical sensors. Fluid microsystems are used for the drugs delivery systems and water treatment; pressure meters find application in scuba diving; pressure sensors are used to monitor and control the industrial production; small speedmeters are used in the bicycle computers; digital pressure meters constantly test the tire state; sensors will be installed on washing machines, vacuum cleaners and even in sport shoes for damping control and for mine detection. The figure 4.3 shows some MEMS application fields:
4.2 Actuators families

One of the most active development field of the MEMS, is the creation of microsensors; difficulties exist in the miniaturization of actuators (Fluitman96), due to both manufacture processes and scaling effects; as the parts get smaller, inertial (volumetric) forces tend to loose their dominance over surface effect forces such as Marangoni’s effect and electrostatics. Different criteria can be used to classify the actuators (Fig. 4.4).

<table>
<thead>
<tr>
<th>FIELD</th>
<th>FEATURES AND ADVANTAGES</th>
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<tbody>
<tr>
<td>medical field</td>
<td>quick diagnosis, gently treatments</td>
</tr>
<tr>
<td>automotive technology</td>
<td>intelligent microsystems, lower energy consumption</td>
</tr>
<tr>
<td>conventional manufacturing</td>
<td>increase of safety monitoring and control</td>
</tr>
<tr>
<td>military field</td>
<td>small and reliable pressure, speed, altitude displayers</td>
</tr>
<tr>
<td>consumer product</td>
<td>Higher performances and lower prices</td>
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</table>

**Figure 4.3 – MEMS application fields**

**Figure 4.4 – Transducers classification**

<table>
<thead>
<tr>
<th>WORK</th>
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<th>thermal</th>
<th>electric</th>
<th>dL = F · δx</th>
<th>OUTPUT</th>
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</thead>
<tbody>
<tr>
<td>Intensive variables</td>
<td>p</td>
<td>T</td>
<td>V</td>
<td>→</td>
<td>F(M)</td>
</tr>
<tr>
<td>Extensive variables</td>
<td>δQ</td>
<td>δS</td>
<td>δI</td>
<td>→</td>
<td>δx(δφ)</td>
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<th>OUTPUT</th>
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<tbody>
<tr>
<td>Intensive variables</td>
<td></td>
<td></td>
<td></td>
<td>dL = F · δx</td>
<td>ACTUATION</td>
</tr>
<tr>
<td>Extensive variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>direct hybrid</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POWER</th>
<th>hydraulic</th>
<th>thermal</th>
<th>electric</th>
<th>W = F · v</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensive variables</td>
<td>P</td>
<td>T</td>
<td>V</td>
<td>→</td>
<td>F(M)</td>
</tr>
<tr>
<td>Extensive variables</td>
<td>Q</td>
<td>S</td>
<td>I</td>
<td>→</td>
<td>v(ω)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LEGEND</th>
<th>p = pressure</th>
<th>T = temperature</th>
<th>V = tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>W = power</td>
<td>δQ = flux</td>
<td>δS = heat</td>
<td>δI = charge</td>
</tr>
<tr>
<td>v = speed</td>
<td>dL = work</td>
<td>F = force</td>
<td>δx = displacement</td>
</tr>
</tbody>
</table>

4-4
An actuator can produce work either generating displacement or force, some of the actuators that can produce a force can generate power. The actuators described in this survey are ordered following this criteria; actuators that produce displacements, actuator that can produce force but not power, and actuators that generate power.

### 4.3 Actuators able to generate displacements

#### 4.3.1 – Multilayer piezoelectric actuators

A piezocrystal modifies its geometry when electric voltage is applied. This effect is used in actuators. The word “piezo” is derived from the Greek word for pressure. Discovered in 1880 by Jacques and Pierre Curie, piezoelectric materials create an electric charge when mechanical stress is applied. Initial experiments with quartz showed that an electric field applied across the crystal would generate mechanical strains as well. This is called the inverse piezoelectric effect and is the working principle of all piezoelectric actuators. The ceramic lead zirconate titanate (PZT) is the most common material used to make piezoelectric actuators. Typical values for maximum strains achieved along the direction of applied field are around 0.1%; one common way to reduce the applied voltage to more practical levels is to use multilayer ceramics. Thin layers of PZT material (20 to 100 µm thickness) are stacked together (Yasin00) and electrically connected in parallel (Fig. 4.5). Tension can be for example 100 V. Sub-nanometer resolution is achievable; for this reason, this kind of actuator is adopted for many high accuracy applications when small displacement is needed. PZT actuators have high stiffness and have a controlled bandwidth of several kHz. Actuator designs for higher displacement usually employ a mechanical leverage to increase the traveled distance; typically, a mechanism working close to a cinematic singularity is used for high
magnification.

**Figure 4.5 – Piezoelectric linear actuator**

### 4.3.2 – Comb drive

Comb drive is an electrostatic linear actuator. The translating part has a spine shape with several fingers shuttle. Fixed finger electrodes are interposed between each set of shuttle fingers. Electrostatic force is exerted between the fixed and the translating fingers. To get high output forces, it is possible to apply high voltage; the restriction here is discharge voltage. However for separations in the 1 µm region the discharge level is sometimes brought down to the 10 - 100 V region. Electrostatic comb drives, which combine large force and medium range (ca. 10 µm), are developing as one of the generic structures in microactuators, applied in accelerometers, gyroscopes, electromechanics filters, micro xy-stages, sacrificial fine positioners, etc. The comb drive of the figure 4.6 is manufactured by surface micro machining. The polysilicon structure has a thickness of 5 µm, gaps of 2 µm between the teeth (Fluitman96).

**Figure 4.6 – Comb drive linear motor**
4.3.3 – Electrostrictive actuators

Magnetostriction (Electrostriction) is the deformation of a ferromagnetic (ferroelectric) material under the influence of a magnetic (electric) field. Electrostrictive polymers have been investigated to generate muscle-like actuation and other types of actuation (Fig. 4.7). Electrostrictive crystal actuators use the stack design where the displacement is a superposition of the strain from several thin crystal layers. Unlike piezoelectric ceramics, for example PZT, electrostrictive crystals are not poled. Positive or negative voltage results in a displacement in the direction of the applied electric field, regardless of the polarity. The strain of the electrostrictive ceramics is in the same order as the strain of the piezoelectric ceramics. The electrostrictive ceramics provides better characteristics of hysteresis and creep. But their strain sensitivity to temperature is much higher.

Figure 4.7 – Electrostrictive polymers

4.3.4 – Elastomeric dielectric actuators

Elastomeric dielectric actuators has been studied at SRI International, USA. Their basic functional element is a thin elastomeric polymer film sandwiched between electrodes. When voltage is applied to the electrodes, electrostatic force compresses the film. Like the piezoelectric element, the basic element of the elastomeric actuation can be used in different designs. Film layers may be actuated in stacks, extenders, tubes or rolls.
4.3.5 – Magnetostrictive actuators

Among the para-magnetic materials Terfenol-D has been the most widely used in magnetostrictive actuators as a highly magnetostrictive material. The actuator is typically composed of a magnetostrictive rod placed inside a coil. When a magnetic field is not applied, the magnetic domains orient randomly in all directions. A current inside the coil produces a magnetic field that elongates the rod, as the magnetic domains are arranged in the direction of the magnetic field. The main disadvantage of magnetostrictive actuators are their small displacements. In some solutions, the magnitude of the strain is about two times larger than the strain of a stacked piezoelectric actuator. Magnetostrictive actuators offer very large output forces and quick dynamic responses.

4.3.6 – Shape memory alloys actuators

Shape memory alloys are metallic materials with a unique ability to change their shape at their transformation temperature. When the metal is deformed and then heated above this temperature it recovers its original shape; during recovery it is able to exert a large force. Nickel-titanium (Ni-Ti) is the most common type of shape memory alloy on the market today. The basis for the shape memory effect is the phase transformation that the crystal structure of the alloy exhibits when its temperature goes above or below its transformation temperature. Below the transformation temperature alloys are in a soft martensite phase and can be deformed up to approximately 8 percent. Above the transformation temperature martensite phase is transformed into a stronger austenite phase (Fig. 4.8). The soft martensite phase can be deformed easily and upon transformation to the austenite phase the material recovers the undeformed shape; the phenomenon presents an hysteresis behavior.
NiTi alloys have 51% nickel and 49% titanium. Higher quantity of nickel strongly depresses the transformation temperature and increases the yield strength of the austenite. Other frequently used metals are iron and chromium (to lower the transformation temperature), and copper (to decrease the hysteresis and lower the deformation stress of the martensite). The transformation temperature of NiTi alloys can be adjusted from over 100 °C to cryogenic temperatures. Actuators using the shape memory effect are mostly linear. Usually, SMA material in wire form is strained by a bias force exerted by a spring or deadweight. Upon heating, which is almost always done by passing current through the wire, shape recovery occurs. Strain is usually limited to 4% to avoid reduction in shape recovery after many cycles. Heating the alloy with current is relatively fast, however the cooling phase, which is usually unforced, is slow. Actuators capable of 4 cycles per second have been reported that use SMA wire both for actuation and bias force. The biggest advantage of SMA based actuators is their simplicity and thus reliability. Also the power to weight ratio is high. However, they are usually on-off type actuators without proportional control.
4.3.7 – Electro-rheological and magneto-rheological actuators

Electro-reological fluids (ERF) are made from suspensions of an insulating fluid base and particles on the order of one tenth to one hundred microns in size; fluid and particles have different dielectric constants. In the presence of an electric field, the particles, due to an induced dipole moment, will form chains along the field lines allowing the ERF to change consistency from liquid to gel. Response time is on the order of milliseconds. Rheological fluids offer the following advantages: quick response, easiness of use, relatively large forces transmission, small size, light weight. However, there are two main drawbacks with these actuators: large voltages are required to produce the output forces and these actuators can only be used to create a variable compliance structure. This means that the output force is obtained as a reaction to an input force from a human operator or the environment. Devices designed to utilize ERFs include shock absorbers, active dampers, clutches, adaptive gripping devices, and variable flow pumps. An example of an ERF is the electro-rheological fluid LID 3354, manufactured by ER Fluid Developments Ltd. The application of ERF’s in robotic and haptic systems has been very limited. Magnetorheological fluids act very much like electrorheological fluids, except that their flow rate is controlled by the strength of a magnetic field, instead of electric field.

4.3.8 – Pneumatic rams

It is possible to create translational and rotational fluid actuators; first micro fluid actuators derive from miniaturization of classical fluid devices. There are some problems about the ‘sealing’ of micro pneumatic pistons; sealed air chambers are difficult to produce. For this reason it is preferable to create deformable chambers instead of sliding piston chambers.
4.3.9 – Bourdon pipe

The Bourdon pipe (Fig. 4.9) is a special actuator able to describe, with its extremity, a circumference (with a positioning error of 6/1000 degree). It has a cylindrical shape; internally the cylinder is subdivided into three chambers individually inflatable (Anthierens00). Inflation of each chamber produces actuator bending.

4.3.10 – Artificial muscles

Artificial muscles are other interesting actuators powered by fluid energy. The muscles are formed by inflatable chambers (Anthierens00); when inflated, muscles provide linear motion. Like human muscles, artificial muscles are able only to pull, so usually each muscle needs to work with an antagonistic one (Fig. 4.10). It is possible as well to use, as fluidic actuators, metallic inflatable chambers.
4.3.11 – Thermal expansion

Thermal actuators are based on the principle of solid, liquid or gas dilatation. Heating can be provided using an electric resistance. Bimorph thermal actuators are formed by two layers of materials with different thermal properties. A long lever can be used to magnify the small thermal elongation. The same principle can be used for fluids; it is possible for example to create a micro piston putting a small bubble of water inside a deformable box and heat it until it evaporates. Some microvalves are driven by thermal actuation. Valve closure is obtained by heating (using an electric resistance), a liquid inside a membrane; membrane dilatation covers the valve outlet. Due to dissipation effects, the power consumption, compared to the mechanical output, is still high.

4.4 Actuators able to generate forces

4.4.1 – Micro linear motor

Thanks to lithographic technology, it is possible to create micro electromagnetic linear motors. The market for linear microactuators is potentially high. Typical specifications for these devices are; output force of at least $1 \times 10^{-3}$ Newton, strokes of at least $100 \times 10^{-6}$ m, fundamental resonance above 1 KHz and dissipation less than $1 \times 10^{-8}$ Watt. The most difficult specification is power dissipation. Figure 4.11 shows an example of micro motor; each of the two air gaps is 5 μm wide, voltage is limited to 25 mA to avoid overheating. A 500 windings coil is necessary to produce a magnetic field of 1 Tesla (Fluitman96). Cost and technology issues suggest that such a coil should be wound and not integrated.
4.4.2 – Solenoids

Solenoids move an iron element attracting it by means of a magnetic field generated by an electric coil (Fig. 4.12). Solenoids have a slow electromechanical constant because coil actuation is quick. These actuators are often used as cheap solutions in mechanical limit switch.

4.4.3 – Voice coil motor

Voice coil motor is formed by a free coil positioned in the middle of a static magnetic field generated by a permanent magnet (Torres00). Electric current, crossing the windings, generates a magnetic force that moves the coil (Fig. 4.13). Linear and rotational actuators can be designed using this principle. For example voice coil motors are used to position the head of hard disks, to actuate the music speakers, to position...
mirrors inside the laser printers and to drive an integrated circuit wire bonder for semiconductor manufacturing. Voice coil actuators can achieve acceleration rates up to 100s of Gs; bonders can raise bonding speed to 22 single bonds per second.

![Working principle of voice coil actuators](image)

**Figure 4.13 – Voice coil motors**

### 4.5 Actuators able to generate power

#### 4.5.1 – Ultrasonic motor

Ultrasonic motors have a rotor positioned on a stator, made of piezoelectric material. The stator, excited by a voltage signal, generates traveling waves and causes a rubbing (stick slip) movement between the stator and the rotor. Figure 4.14 illustrates the working principle. Typical characteristics of these motors are high torque at low speed and high holding torque due to friction between stator and rotor. Ultrasonic motors are also suitable for hazardous environments since no sparks are produced. The inherent high torque at low speed eliminates the need for a complex gear box in many cases. Typically, the ultrasonic motor is excited by two sine waves 90 out of phase, with an amplitude exceeding 100 V (Yesin00). Although the motor can be constructed in small size, the necessary electronics to generate the drive signals is quite complex.
4.5.2 – Inchworm piezoelectric motor

Bimorph piezoelectric actuators are obtained joining two piezoelectric layers: an isolating material is interposed between the two layers. Bimorph can be bent or elongated energizing independently the two piezoelectric layers. Using bimorph actuators, it is possible to create a inchworm piezoelectric motor (Anthierens00). A set of bimorph actuators is disposed on the motor stator along a circumference. Small and synchronised rotations of the bimorphs give continue rotation to the rotor (Fig. 4.15).

4.5.3 – Comb drive

When a difference of voltage is applied between two conductive parallel plates, attractive electrostatic forces born on the plates (Coulomb law). The field strength depends on gap size and surface roughness (Fig. 4.16). Electrostatic fields can exert great forces, but generally across very short distances. Linear electrostatic actuators generate comparatively small strokes. Thus, multilayered structures have to be used.
Since electrostatic force increases with the distance between the surfaces, the surfaces are designed as close as possible. Thanks to micromachining, the electrostatic actuator force can be increased, minimizing the distance between the two electrodes. Even a dust particle, inserted in a small air gap, can cause breakdown.

\[
F = \frac{1}{2} \cdot \varepsilon \cdot A \cdot \left(\frac{V}{d}\right)^2
\]

\(F\) = force \(\varepsilon\) = dielectric constant \(A\) = electrode area \(d\) = electrodes distance \(V\) = voltage

Figure 4.16 – Coulomb force

Comb drivers can be linear or rotational; the number of poles in a rotating comb drive is much smaller than in linear one. For this reason the torques generated is limited (about 10^{-11} Nm, motor radius of about 100 µm). Only a small amount of power can be delivered, due to the motor internal friction, therefore the application might be restricted to “free running“ devices, e.g. rotating mirrors or gratings, or storage disks. Electrostatic actuators are still under development.

4.5.4 – Wobble motor

Wobble motor is a variable gap electrostatic motor that generates rolling motion of the rotor on eccentric stator without slip. The stator of the actuator sketched in figure 4.17 hosts 3 pairs of poles. When a pole is powered, it attracts the rotor; the alternative powering of the poles generates the rotor rotation. For example a Wobble motor can have an external diameter from 1 to 3 mm, an air gap of a few microns, and a reduction of 1:3000. This kind of actuator, powered by 200 V, gives a torque from 0.5 to 2 µNm @ 10 revolutions for minute (Anthierens00). There is a wide range of materials that can
be used as poles. The rotational motion of this actuator, by means of gears, can be transformed in linear motion (Fluitman96).

**Working principle**

**Prototype**

*Figure 4.17 – Wobble motor*

### 4.5.5 – DC motors with brushes

When current flows through a conductor or coil, an electromagnetic field is generated. This effect is often used for magnetic actuators. All electric motors convert electrical energy to magnetic and then to mechanical (Fig. 4.18). Electromagnetic devices offer low cost and easy applicability (Yesin00).

*Figure 4.18 – Electromagnetic motors family*
Miniaturized motors can produce linear and rotational motion. Figure 4.19 shows the basic types of electric motors.

\[ F = I \cdot L \times B \]

**Lorentz Law**

\( F = \text{net force} \)
\( I = \text{electric current} \)
\( L = \text{coil length} \)
\( B = \text{magnetic field} \)

**Figure 4.19 – Lorentz Law**

As the diameter of the motor increases, its circumference increases, enabling the designer to place more windings. A general relationship between motor size and torque capabilities can be stated as (Fig. 4.20):

\[ T = 2 \cdot F \left( \frac{D}{2} \right) = kDL \]

\( T = \text{torque} \)
\( k = \text{constant} \)
\( D = \text{coil diameter} \)

**Figure 4.20 – Torque equation**

Miniaturization of the electric motor is not advantageous since the torque output decreases by the square of the linear dimension. Still, with efficient design and new permanent magnets with high magnetic field density, DC electric motors are feasible at very small size. The introduction of Alnico and Ferrite magnets in early 1940’s, and the discovery of rare-earth magnets in 1960’s enabled motor manufacturers to decrease the size of permanent magnet motors while increasing power capacity and decreasing costs. Development of NdFeB (Neodymium-Iron-Boron) magnets promises a source of high energy magnetic materials with relatively plentiful sources. DC motors are widely used in robotics and other servoing applications due to the ease of their control (Yesin00); there is a linear relationship between motor torque (load) and speed at a fixed voltage.
Similarly, voltage is related linearly to speed at a constant load (Fig. 4.21).

![Figure 4.21 – DC motor torque speed plot at nominal voltage](image)

Maximum efficiency of energy conversion occurs at about 10% of the stall (zero speed) torque, however, the maximum power output occurs midway through the speed-torque graph.

Coreless motors get their name from the fact that there is no iron core in the armature (rotor). Instead of being supported by an iron core, the windings are held together in a rigid structure by a thermosetting plastic (Torres00). As a result, the armature is hollow, and the permanent magnet can be mounted inside of the coil (Fig 4.22).

![Figure 4.22 – Coreless motor](image)

The coils are placed around the permanent magnet: when electric current runs into the coils in a static magnetic field a magnetic force is created. The current is applied to the
Actuation innovative technologies

coils using brushes and commutator. The brushes ride on the commutator surface and provide a sliding contact through which current is switched to the various commutator segments and coil windings at the appropriate times to produce torque. Because of small motors brush/commutator systems are generally made by precious metal, the voltage drop between brushes and commutator is generally very small; hence motors can be manufactured to operate at very low voltages. The disadvantage with these motors is that brushes generate dust and sparks.

4.5.6 – Brushless DC motor

Brushless motors instead of brushes use a control circuit. Brushless DC motor has a stationary magnet and a rotating armature powered by brushes; brushless DC motor has a rotating magnet and a stationary armature (Yesin00, Torres00). Windings are part of the housing and can be energized without requiring a commutator-and-brush system (Fig. 4.23).

![Figure 4.23 – Brushless DC motor](image)

A brushless motor doesn’t create dust or sparks; this advantage can be useful for example in explosive, medical or food environments. As the size (and thus torque output) decreases, the effect of frictional losses at the brushed commutator increases. Brushless motors, therefore, have the advantage of increased efficiency over brushed ones; the smallest brush motor has an 8 mm diameter while the smallest brushless
Chapter 4

motor has (5 to) 1.9 mm diameter. Commutation can be operated using Hall elements (servo motor) or counter electro magnetic field (non servo motors); in the figure 4.24 is reported a comparison between the two kind of motor.

<table>
<thead>
<tr>
<th></th>
<th>Servo motors</th>
<th>Non servo motors</th>
</tr>
</thead>
<tbody>
<tr>
<td>description</td>
<td>The Hall elements, inside the motor, detect the rotor field and create accurate control signals. Its driving system needs less electronic components.</td>
<td>The counter electro magnetic field, from outside of the motor, analyzes the shape of back electro magnetic field</td>
</tr>
<tr>
<td>advantages</td>
<td>An encoder or resolver, provides high resolution (comparable to DC motor with brushes). Low power consumption</td>
<td>It is easy to implement. It is “inaccurate” and recommended mainly for high-speed continuous operation.</td>
</tr>
</tbody>
</table>

*Figure 4.24 – Servo and non servo DC motor comparison*

### 4.5.7 – Stepper motors

A stepper motor converts electrical pulses into specific rotational movements. The motion created by each pulse is accurate and repeatable. The rotor is made by a permanent magnet, the stator is formed by coil windings and magnetically conductive stators. Energizing a coil winding, an electromagnetic field is generated with a north and south pole as shown in figure 4.25 (Torres00). The stator establishes the magnetic field, which causes the rotor to align itself with the magnetic field. The rotor magnet, aligning itself to sequentially energized stator coils, rotates. Rotor and stator need to have the same number of pole pairs. The rotary motion of a stepper motor can be converted into linear motion for example using rack & pinion.
The Haydon Switch and Instruments (HSI) offers bipolar linear stepper motors that move with linear increments of tens of micrometers; the inside of the rotor is threaded and a lead screw replaces the shaft. The motor has 10 mm total displacement with 12 \(\mu m\) resolution (Fig. 4.26). It is possible to drive the motor by microstepping, which improves the resolution; each full step of the motor is subdivided into smaller steps.

Api Motion conceived a disk stepper motor that has permanent magnet in the rotor and electro magnets in the stator (Fig. 4.26); this design highly decreases the rotor inertia (Torres00).
4.5.8 – Micro stepper motor

Rotational magnetic microactuators with variable reluctance have also been built. Rotor tip forces are nearly identical with the output forces of miniature linear actuators. Figure 4.27 shows a 3-phase stepper motor provided with idle gear and single phase electromagnetic brake (Fluitman96). Maximum rotational speeds of 150,000 rpm in air for 3 month testing of 120 µm diameter rotors and 16,000 rpm for 2 mm diameter rotors have been shown. Torques up to $10^{-5}$ Nm have been measured. Some requirements have to be investigated to allow the microactuators development; new processing tools, cost control of the tool, new permanent magnetic materials (to decrease power dissipation), more advanced motors designs (today the design is primitive and ineffective).

![Micro stepper motor](image_url)

**Figure 4.27 – Micro stepper motor**

4.6 Actuators comparison

There are many types of actuators that can be used for the design of small robots. To each of the actuators corresponds a proper size that guarantees an optimal energy efficiency. For each actuator it is important to take into consideration its performance, efficiency, easiness of use, power requirements, machining costs and on site performance. To facilitate the actuators selection, four figures are provided; figure 4.28
summarizes the main advantages and disadvantages of each actuator, figure 4.29, 4.30 and 4.31 compare the actuators salient physical properties (Sommer98).

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Main use</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric</td>
<td>Rotation, translation</td>
<td>• High torque at low speed and high holding torque at zero power (ultrasonic)</td>
<td>• High voltage and special waveform required.</td>
</tr>
<tr>
<td></td>
<td>deformation</td>
<td>• High bandwidth (kHz)</td>
<td>• Have low strain, rotation and deformation (% 0.1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High power/weight ratio</td>
<td></td>
</tr>
<tr>
<td>Electrostatic</td>
<td>rotation</td>
<td>• High torque at low speed</td>
<td>Motors have only micron size</td>
</tr>
<tr>
<td>Magneto- and electro-strictive</td>
<td>translation</td>
<td>• Some electro-strictive polymers have muscle-like performance (high power/weight ratio)</td>
<td>• Magneto-strictive have low power/weight ratio, low displacements, are difficult to use</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Electro-strictive polymers are new and not sufficiently tested</td>
</tr>
<tr>
<td>Thermal</td>
<td>translation deformation</td>
<td>• High power/weight ratio</td>
<td>• Low displacements</td>
</tr>
<tr>
<td>Shape Memory Alloy (thermal)</td>
<td>translation deformation</td>
<td>• Simple and robust</td>
<td>• Low strain (% 4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High actuation force</td>
<td>• Low bandwidth (&lt;1 Hz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Simple two-state (on/off) action</td>
<td>• Inefficient with batteries</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relatively high elongation</td>
<td>• Requires complex mechanism for position control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Easy to install, to produce and to use</td>
<td>• Not usable in all environments</td>
</tr>
<tr>
<td>Electro- and magneto-rheological</td>
<td>viscosity change</td>
<td>• Simple to use</td>
<td>High voltage required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High bandwidth</td>
<td>• Transmit, doesn’t make power</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Still at study level</td>
</tr>
<tr>
<td>Electro-Magnetic</td>
<td>rotation</td>
<td>• Different size and types available</td>
<td>Requires gearbox and some electronics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Commercial products are easy to produce</td>
<td>• Low efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Easy to use, to control</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reliable</td>
<td></td>
</tr>
<tr>
<td>Fluid</td>
<td>translation deformation</td>
<td>• High force and displacements</td>
<td>• Difficult to control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Pumps are voluminous</td>
</tr>
</tbody>
</table>

*Figure 4.28 – Actuators characteristics*
Chapter 4

Work

<table>
<thead>
<tr>
<th>Elongation [%]</th>
<th>Force density [kN/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Thermal
Pneumatic
Hydraulic
Shape Memory alloy
Conducting polymer
Piezoelectric, Magnetostrictive
Electrostatic film
Electrostatic gel
Dielectric elastomer
Pneumatic
Muscles

Figure 4.29 – Actuators work density

Power

<table>
<thead>
<tr>
<th>Actuation time [s]</th>
<th>Power density [kW/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,01</td>
<td>1</td>
</tr>
<tr>
<td>0,1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
</tr>
<tr>
<td>50</td>
<td>5.000</td>
</tr>
<tr>
<td>50,5</td>
<td></td>
</tr>
</tbody>
</table>

Thermal
CP electrode, IPN
Solenoid
Electrostatic film
Electrostatic gel
Muscles
Solvent change
pH change
Collapse in electric field
Shock in electric field
CP electrode, IPN
Shape Memory alloy
Dielectric elastomer
Piezoelectric, Magnetostrictive
Electric motor
Conducting polymer

Figure 4.30 – Actuators power density
### Table: Actuators Performances

<table>
<thead>
<tr>
<th>Actuator Type (specific example)</th>
<th>Max (%)</th>
<th>Max Pressure (MPa)</th>
<th>Specific Elastic Energy Density (J/g)</th>
<th>Elastic Energy Density (J/cm³)</th>
<th>Coupling Efficiency k² (%)</th>
<th>Max Efficiency (%)</th>
<th>Specific Density</th>
<th>Relative Speed (full cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic PZT</td>
<td>0.2</td>
<td>110</td>
<td>0.013</td>
<td>0.10</td>
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<td>0.13</td>
<td>1.0</td>
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<td>7</td>
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<td>Integrated Force Array</td>
<td>50</td>
<td>0.03</td>
<td>0.0015</td>
<td>0.0015</td>
<td>−50</td>
<td>&gt; 90</td>
<td>1</td>
<td>Fast</td>
</tr>
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<td>70</td>
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<td>0.025</td>
<td>−</td>
<td>60</td>
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<tr>
<td>PVDF-TrFE</td>
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<td>0.17</td>
<td>0.3</td>
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<td>−</td>
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<td>Fast</td>
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<tr>
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<td>&gt; 5</td>
<td>&gt; 200</td>
<td>&gt; 15</td>
<td>&gt; 100</td>
<td>5</td>
<td>&lt; 10</td>
<td>6.5</td>
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<td>TiNi</td>
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<td></td>
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<td></td>
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<td>Fast</td>
</tr>
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<td>3.4</td>
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<td>90</td>
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<td>Fast</td>
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<tr>
<td><strong>Shape Memory Polymer</strong></td>
<td>100</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>−</td>
<td>&lt; 10</td>
<td>1</td>
<td>Slow</td>
</tr>
<tr>
<td>Conducting Polymer</td>
<td>450</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>&lt; 1</td>
<td>&lt; 1%</td>
<td>−1</td>
<td>Slow</td>
</tr>
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<td>0.06</td>
<td>0.06</td>
<td>−</td>
<td>30</td>
<td>−1</td>
<td>Slow</td>
</tr>
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<td><strong>Mechano-chemical Polymer/Gels</strong></td>
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<td></td>
<td></td>
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<td></td>
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<tr>
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<td>&gt; 35</td>
<td>1</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Natural Muscle</strong></td>
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<td>0.07</td>
<td>n/a</td>
<td>&gt; 35</td>
<td>1</td>
<td>Medium</td>
</tr>
</tbody>
</table>

*Figure 4.31 – Actuators performances*
4.7 MEMS demonstrators

A few years ago first MEMS demonstrators made their first comparison. The main task of the demonstrators is to show the MEMS capabilities (Jager00). Usually the Universities make small size walking robots using MEMS (Laksanacharoen00, Yeh00). It is interesting to analyze the technical solutions adopted for the design of these small and complex robots. Two examples are hereafter reported.

The spy robot is a robot developed for defense purposes (Fig. 4.32). A crawler main robot sends several spy robots in the place to explore; every spy robot, equipped with a video camera, is able to move autonomously (Yesin00). The camera is adjustable using two small electric motor, the video signal is sent to the main unit. This small robot is able to jump to overcome small obstacles. There is a prototype of spy able to throw a small wire and to climb on it. The device uses micro DC motors for the motion.

The flying insect, powered with piezoelectric unimorph actuators, has small electric batteries recharged by small solar panels (Fig. 4.33). The insect has two wings; each wing is actuated by two four bar frames independently actuated (Yan01). This insect has image and force sensors. Like the spy robot, the flying insect is controlled by a CPU integrated in the robot.

Figure 4.32 – Spy robot

Figure 4.33 – Flying insect
Chapter 5

Early prototype settings

The aim of this chapter is to present in detail the MIRS environment with its typical components and technologies that addressed the PhD thesis research work. Some of the early prototype solutions are described and discussed. This recalled preliminary work required to orient and tune my service robotics competences to the surgical robotics tools specifications. The discussions with field experts were useful and precious in addressing the design methodology future work.

When designed for minimal invasive surgery robotic arms need to be conveniently miniaturised and to accommodate all required capabilities. For example operating theatres are required:

- to manipulate the gastrointestinal tracts, requesting dextrous co-operating handling;
- to locate, debride or repair trauma due to metal objects or shrapnel lodged in the abdomen;
- to blunt dissect, to locate cancerous growths or stones in the pancreatic ducts and thus
treat pancreatitis;

- to perform internal anastomosis, or to join, suture and knot tie sections of intestine;
- to detect embedded structures or to divide, push or pull anatomic pieces.

There are some advanced procedures, like catherisation, that can be completed, from surgeons, only by hand. The task of the thesis is to design new surgical instruments suitable for laparoscopic operations; despite surgical robots performing laparoscopic operations already exist (Chapter 3), there is need of dexterous instruments enabling to simplify the achievement of complex surgical operations.

The instruments are designed using a modular approach: all the instruments are formed by the same main articulated mini-arm and an end effector (Chapters 6 and 7). The mini-arm, formed by the assembly of several basic modules, has a snake like shape. One of the two extremities of the mini-arm is firmly fixed to the external part of the body to be operated, the other carrying the end-effector, is inserted into the body. Several types of end-effectors have been designed, each able to perform a different task; some examples are scissors, video camera and sewing machine.

There are antagonistic constraint about the worm size. The diameter of the worm needs to be small to allow an easy insertion between the ribs and among the organs (Fig. 5.1);
the length of each worm module has to be short to allow a good dexterity inside the body, the size of the worm has to be big enough to transmit the forces necessary for the operation. The connection between the robot mini-arm and its end-effector is crucial; we can call this connection “wrist”.

The task of this project is to design a dexterous snake shape wrist, able to transmit the mechanical power necessary to perform many kind of surgical operations. A similar task has been solved from the Poland surgery tool (Fig. 3.36). Professor Filaretov, from Russian academy, thanks to his long robotic experience, added a valuable contribution during the design of the mini-arm and of the end effectors.

The endoscope design is a complex task; there are strict space constraints, high motion requirements, control needs to be accurate, moreover the overall system reliability needs to be outstanding. It is necessary to use materials well tolerated by human organs.

Different kind of knowledge are request to complete the robot design: the problem can be solved only by a multidisciplinary team.

5.1 – Surgical robot components and technologies

Surgical robots are formed by components usually deriving from industrial robots. Only recently companies are starting to develop motors, sensors and instruments especially devoted for this field. For medical robots, the implementation of sensors and of an intuitive human robot interface is crucial. In Chapter 3 surgical robots are described as a “whole”; some of the possible components/technologies needed to form a surgery robot are now examined.

5.1.1 – Remote operation facilities

Remote surgery is a specific type of robotic surgery where the actions of the robot are
not autonomously defined, rather controlled in real-time by the surgeon. The study of surgical remote operations has been performed mainly for military purposes. This technology can be used as well to allow very skilled surgeons to operate in different countries from the same virtual theatre room. Visual, aural, force and tactile feedback is provided to the surgeon by the robot. In telesurgery the patient is usually imaged before the operation starts and the information sent to the surgeon. Fiducials are often used as a means of aligning the virtual image with the actual position of both the robot and the patient. In addition to that, infra red transmitters and receivers can be adopted. It is important to notice that the distance between the virtual and the real operation theatre, influences the time lag of the sensors feedback. One way to overcome this problem, is to increase the amount of the operation that can be executed automatically from the end effectors of the surgical robot.

Remote operation can increase accuracy; while human hands generally make movements of the range of centimetres, often it is necessary to move some surgical tools just a few millimetres. Thanks to teleoperation, it is possible for example, during an eye operation, to scale the movement between the master and the slave of a factor 0.2.

5.1.2 – Virtual reality

Virtual reality is an efficient training instrument (Section 3.5); the physician is immersed in a virtual world; he handles virtual instruments, sees stereoscopic images and feels force feedback. Acoustic signals and digital voice can give advised and remarks about the virtual operation in progress. Simulation is an essential element in remote surgery in which communication time delays are significant. Training in the operating room increases risk to the patient and slows the surgery procedures; computer-based virtual training has many potential advantages.
5.1.3 – Virtual glove

Robotic surgery finds wide fields of intervention. The interface between the surgeon and the robot is crucial in conventional surgery, micro-surgery and teleoperation. The virtual reality glove is a device often used for teleoperation. The glove, uses flex-controlled potentiometers or optical fibres, to sense the pose of the surgeon's hand and fingers. Alternatively, the surgeon hand movement is not registered, rather the position of a handle the surgeon manipulates; this solution is for example adopted for teleoperation at the Jpl (Jet Propulsion Laboratory) Endo-assist arm is driven by the surgeon head movements (Fig. 3.15).

5.1.4 – Computer tomography

Computer tomography (CT) is the main method for accomplishing the imaging of the patient. Cross-sectional views of the patient are created by means of magnetic resonance imaging or x-ray methods. Images are then converted into a 3D model of the patient.

5.1.5 – Intra-surgical registration

The patient is secured in position on the surgery table; in order to safely guide the robotic movements, a common reference frame between the pre-surgical data and the corresponding patient anatomy must be established. This process is called intra-surgical registration and can be achieved by two primary techniques. Pre-operative data can be compared with physically implanted markers to the underlying patient (fiducials attachments); this technique requires for the patient, additional trauma. Lately, new non invasive registration methods have been introduced; an example is surface based registration. From preoperative data are extracted mathematical curves and surfaces describing the patient body. The position of the patient is found and track comparing and matching real time the intra-surgical data with the extracted curves.
5.1.6 – Stereoscopic view

The use of stereographic images finds many applications in service robotics. For example, a 3D real-time navigation system can be used for wheelchair navigation. Stereoscopic view allows to create three-dimensional images of organs from two or more 2D radiographies; this 3D model helps the surgeon, during the operation, to see details otherwise not directly visible. Moreover, virtually reconstructed organs, can be implemented inside surgery simulation programs. New training is necessary each time a new robot-human interface software is released or a new medical instrument is developed.

5.1.7 – Laparoscopic camera

MIS adopts small laparoscopic video cameras to monitor surgery procedures (Fig. 5.2). The born and development of active optics, including fibre optics, CCD imagers, and CRT displays, has widened the MIS frontiers. One or more cameras can be inserted simultaneously into the patient body, each through a small incision. New laparoscopic cameras have zoom capability, are handled by robotic arms and are directly controlled by the surgeon voice, by a foot pedal, or by the movements of the surgeon head. Robot arms increase the image stability and eliminate the need of a camera assistant. The combination of data from two or more laparoscopic cameras give to the surgeon a binocular stereoscopic view. Some surgery platforms allow to save and later quickly retrieve the preferred laparoscopic camera positions.

Parallax effect lowers the surgeon depth perception; this problem can be overcome moving slightly the camera while it keeps looking the surgery operation.

During remote surgery, the surgeon needs at least the following information; laparoscopic camera view, overall view of the operating room, and patient monitoring.
data. These real and synthetic images can be tiled onto a "virtual dome" so that as the surgeon looks around, he or she sees a cohesive environment (Fig. 5.2).

Figure 5.2 – Laparoscopic camera

5.1.8 – Parallel kinematic robots

Surgical operations, like brain surgery, require high accuracy; this need suggested the IPA Fraunhofer Institute to replace classic surgery robots with parallel kinematic robots (Fig. 5.3).

Figure 5.3 – Parallel robot for brain operations

Operation resolution can be further enhanced splitting the tasks; the actuators that power the parallel platform are used for gross positioning, the actuator mounted on the parallel platform and driving the surgical instrument is capable of fine positioning.

5.1.9 – Laparoscopic scalpel
The harmonic scalpel is a versatile laparoscopic instrument able to simultaneously cut and coagulate; it can be used as retractor, grasper, pointer, sharp dissector, and blunt dissector. Figure 5.4 shows a classic laparoscopy harmonic and coagulation scalpel.

![Figure 5.4 – Harmonic and coagulation knife](image)

The scalpel can coagulate, by electric current, only small cuts; for wider openings nail and suturing wire are necessary. The suturing operation is executed by two robot arms having grippers as end effectors. Staplers are popular for ligating vessels (Fig. 3.43).

### 5.1.10 – Grippers

Small grippers are the basic tools that enable manipulation during MIS. Different MEMS micro-grippers exist (Fig. 5.5, Anthierens00).

![Figure 5.5 – Grippers](image)

### 5.1.11 – Infrared transmitter

Surgical robots normally have both cameras and sensors; cameras give an overall view of the scene, while sensors give quantitative information. Stop switches can help to limit
damages due to positioning errors. The robots can be equipped with ultrasound or x-ray sensors, to simplify the recognition or the identification of the patient body.

The use of redundant sensors, offers data redundancy and allows to check the data consistency.

5.1.12 – Biological and chemical sensors

Biosensors have the capability to selectively measure concentrations of substances in fluids and to determine biological parameters, such as toxicity and the effect of allergens. Chemical sensors can detect a specific component in a foreign substance as well as its concentration in this substance.

5.1.13 – Active and passive encoders

Active encoders are often used for the control of the robot actuation. Passive encoders can be employed as input devices; an hand driven arm, equipped with passive encoders, can detect the exact position of the end effector (Section 3.2.3). For example, the position of an echographic plane can be tracked by passive encoders in order to create a three-dimensional image of the organs.

5.1.14 – Vision and force sensors

Tactile sensation is an extremely important issue in open surgery. Important vessels and ducts shrouded in connective tissues are delicate, their presence is easier felt by tact, rather than seen. Force feedback has been introduced in teleoperations to allow an easier interaction between the physician and the outpatient. Eye feedback is important for positioning tasks; a good control can be achieved only coupling eye feedback with a force feedback. The surgeon, grasping with his hands the organs, from their hardness, is able to determine weather or not the organ is healthy.
Integration and prototype settings

5.1.15 – Actuators selection

In the chapter 4 a list of actuators suitable for small robotic devices has been described, it is now interesting to verify which actuators can be embedded inside our 10 mm diameter surgical instrument. Figure 5.6 provides a list of companies that sell respectively: coreless DC motors, Brushless DC motors and Voice coil actuators; for each motor the minimum size available is shown. Data has been collected on February 2003. Figure 5.7 gives data pertinent miniaturised DC motors.

<table>
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<tr>
<th>Type</th>
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<th>M max mNm</th>
<th>Gearbox Ratio (mm)</th>
<th>Effic</th>
<th>Encoder Present</th>
<th>Encoder Ø (mm)</th>
<th>L (mm)</th>
<th>System M St(G) mNm</th>
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5.2 From wrist to articulated mini-arm

The first idea was to create a surgical robot attaching the end effector (for example
miniature grippers), to a “standard” robot using a small wrist. All the attention was focused on how to design a small wrist using MEMS. The following basic constraints have been fixed; overall wrist size should be about $10^3 \text{ mm}^3$ and should have 3 DOF.

It is possible, for example, to design a wrist driven by piezoelectric motors, allowing 3 translations and no rotation (Fig. 5.8). It is possible as well to imagine a Cartesian micro-wrist allowing 2 translations and 1 rotation (Fig. 5.9).

After some additional thinking, it was clear that this type of wrist doesn’t offer enough dexterity to the surgical instrument; for this reason it has been chosen to replace it with an articulated mini-arm.

The mini-arm has a snake like shape. The surgical robot is formed by a classic robot arm on which is assembled the mini-arm carrying the end effector. The modules forming the body of the articulated wrist can be identical or not. Depending on the kind of surgical operation, the number of modules can vary.

Now the design of the mini-arm modules is described. First the module geometry is studied, then its actuation. Each mini-arm module has an architecture that allows one or more degrees of freedom.

Several articulated mini-arms have been conceived. Common lines are addressed, so that
Integration and prototype settings

each device satisfies the following requirements for manufacture and servicing:

- modularity: an individual mini-arm is obtained by replicating a series of reference modules (Walker00), endowed with the requested set of task-specific end-effectors; depending on the kind of surgical operation the number of the modules of the articulated body can vary. The modular design offers economic, reliability and maintenance advantages;

- size: the mini-arm external diameter shall not exceed 10 mm, with a total length of 200 to 600 mm, assuring the body penetration, to the required depth, with acceptable induced damage;

- standardisation: the mini-arm components, including end-effectors, are linked using standard common interfaces; the plug and play interface transfers sensors signals, control signals, power for the actuators and power for the control. Once the interface is defined, any company can design actuation or effector modules, to be integrated into specialised devices.

5.3 Mini-arms review

Example developments are described later summarising typical pros and cons of the resulting set-ups. Four mini-arms prototypes are hereafter presented and discussed. Main features of the ideal articulated mini-arm are: modular expansibility, extended versatility, small diameter, proper torque, high accuracy, high reliability, safe up-keeping and low cost. The class of surgical operations the mini-arm will be suitable for is actually acknowledged by testing the performance of the four mini-arm prototypes.

Rough considerations can exclude some kinds of operations; for example, common sense suggests that a 10 mm diameter mini-arm has a size that is not compatible with
brain operations. The mini-arms proposed are mainly heavy duty, to actuate the surgeon tools (e.g. scalpels, grippers), while a camera mini-arm could be light duty. If miniaturisation of any of the mini-arms attains a sufficient performance it could be convenient, for modularity, to use the same heavy duty mini-arm architecture for all mini-arms including the camera.

5.3.1 – Mini-arm with self-powered modules

A fully modular lay-out considers a sequence (Fig. 5.10) of actuated modules (Fig. 5.10, part 1), articulated through one DoF joints (Fig. 5.10, part 2). A DC motor (Fig. 5.10, part 3), provided with a gear-box (Fig. 5.10, part 4) and encoder (Fig. 5.10, part 5) actuates each joint using a bevel gear transmission (Fig. 5.10, part 6 and 7).

![Figure 5.10 – Mini-arm with self-powered modules](image1)

![Figure 5.11 – Wire-driven mini-arm](image2)

The architecture avails itself of MEMS technology for micro-manufacturing; LIGA-processes offer accuracy of up to 1 µm. Indeed, almost any size from mini- to micro-motors are available; Penn State’s Materials Research Institute makes piezoelectric motors from 1.8 millimetres in diameter and 4 millimetres long; The William Mc Lellan electric motor fits within a cube 0.38 mm on a side (Anthierens00). The micro-
actuator’s torque is often limited because of scaling effects; as parts get smaller, inertial (volumetric) forces tend to lose their dominance over surface effect forces such as electrostatics.

The actually achieved performance is quite noteworthy; for surgery operations requiring comparatively high forces, each mini-arm module can be for example, equipped with the biggest commercially available motor that could fit the overall device size (within the relatively small 10 mm diameter). The main drawback of the mini-arm is its low dexterity: each module has one DoF that allows a limited range (rotation from 0 to 45°). Reliability as well is low: the bevel gear teeth (Fig. 5.10, part 6 and 7) and the gear boxes (Fig. 5.10, part 4) are frail parts.

### 5.3.2– Wire-driven mini-arm with steered clutches

The clutch steered mini-arm (Fig. 5.11), has two DoF modules (Fig. 5.11, part 1), with spherical joints (Fig. 5.11, part 2) and lateral wires (Fig. 5.11, part 3), driven by a motor located at the elbow. Each module is displaced by three wires; the articulation is similar to a human elbow, where the wires and the spherical joint represent respectively the muscles and the articulation. A long rotating shaft transmits the mechanical power into the modules. Each module internally hosts three spools (Fig. 5.11, part 4), the control circuit (Fig. 5.11, part 6) and a short flexible shaft. The long rotating shaft is formed by the union of the sequence of the short module shafts. If for example the mini-arm is composed of three modules each 10 mm long, each module will host a 10 mm shaft; the overall mini-arm length will be 30 mm, the long rotating shaft, running inside the mini-arm will be 30 mm. The modules interface (Fig. 5.11, part 5) provides the mechanical link between the shafts. Each elbow wire is wound on a different spool; for sake of clarity, the broken view of figure 5.11, shows only one wire (of the 3) wound on a spool.
of a solenoid clutch (Fig. 5.11, part 4). All the spools are connected to the main rotating shaft by a different clutch. Each clutch can switch its spool in one of the following states:

a) fixed: spool not rotating,

b) actuated: spool joined to the rotating shaft,

c) free: spool free to rotate.

The shaft rotates always in the same direction, for example clockwise, and at a constant speed. Wire stretching/shrinking is an active phase; a wire can be shortened, switching its spool to the state b. Wire elongation is a passive phase; the clutch of the wire to be elongated is left free (position c) and the other clutches are actuated accordingly. The spherical joint shape (Fig. 5.11, part 2) creates geometrical dependencies between the wire lengths: changing the three wires lengths, it is possible to rotate the spherical joints in any direction.

Example

*******************

Configuration 1 (wire 1 length =1, wire 2 length =1.5, wire 3 length =1)
Configuration 2 (wire 1 length =1.5, wire 2 length =1 , wire 3 length =1)

We suppose that the long flexible shaft, that transmits the motion, turns clockwise; hence, each of the three spools has its wire wound on it clockwise. Each time a spool is positioned in state b, the spool shortens its length. To move from configuration 1 to configuration 2, it is necessary to: shorten wire 2 – spool 2 state b, elongate wire 1 – spool 1 state c, leave wire 3 unchanged – spool 3 state a.

All the operations have to be accomplished simultaneously.

*******************
Integration and prototype settings

Mini-arm stiffness can be increased by simply positioning, at the same short time, all the three wires to state b.

Three kinds of clutches have been designed; solenoid, shape memory alloys (SMA) cylinder and SMA spring clutch (Fig. 5.12, part a, b and c). Each clutch has a spool on which is wound one of the three wires that actuate every spherical joint (of the steered clutches mini-arm). Each solution connects the spool to the rotating shaft using a different technique.

Solution a. Solenoid clutch. It is built, from bottom to top, on the following elements; electric magnet fixed to the module frame, rotating plate joined to the rotating shaft, spring, wire spool and plate joined to the module frame. The spool and the rotating plate are made by ferromagnetic material. When the solenoid is not powered, the spool, pushed by the spring against the fixed plate, doesn’t rotate. Once the solenoid is actuated, the rotating plate attracts the spool and transmits rotation to it.

Solution b. SMA cylinder clutch. The cylinder, using electric current, can be heated. The cylinder is always linked to the spool; normally (no current), the cylinder is linked to the rotating shaft. Heating the cylinder, the connection between the cylinder spool and the rotating shaft is disengaged.

Solution c. SMA spring clutch. The work principle is similar to the Solution b. The spring, if heated, pushes the spool against a rotating plate, enabling the stretching of the wire wound on the spool. This clutch is provided with a sensor: inside the SMA spring is embedded a commercial encoder that detects the angular position of the spool. From this data, it is possible to calculate, out of the total wire length, which portion is wound on the spool and which part is working as “muscle”.

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The mini-arm can carry an end-effector, e. g., a clamp (Fig. 5.11, part 7). The clutch steered mini-arm has limited dexterity, since spherical joints allow bounded rotation spans (-20° to +20°, -20° to +20°). The size of the device depends on the clutches. The rotating shaft is actuated by an electric motor, located in the surgical theatre and outside of the patient body. As the size of this motor is not limited, the joint transmitted force depends only on the clutch characteristics. The mini-arms interface (Fig. 5.11, part 5) provides at the same time, a connection for the mechanical transmission and for the control signals. The short module shafts are joined via a bayonet link. This solution offers good modularity and maintainability capabilities; the interface allows to quickly join together the number of modules required for the specific surgical operation. If during an operation, a module fails, it can be easily disassembled and replaced by a spare one. In any case, it will not be necessary to immediately repair the tool. The device overall reliability is limited; even if the mini-arm has only one actuator, the high number of miniature clutches is certainly a critical issue.

5.3.3 – Mini-arm with universal-joints links

Since the dexterity of the first two mini-arms is limited, a new mini-arm has been conceived (Fig. 5.13). The solution adopts modules (Fig. 5.13, part 1) hosting two DoF universal joints (Fig. 5.13, part 2). Actuation is performed locally, by DC motors or
Integration and prototype settings

externally driven by wires. For reliability and to limit the length of each module, wire actuation is preferred. Each of the two universal-joints DoF is actuated by a wire (Fig. 5.13, part 3); for clarity only one wire and its outer sheath are shown.

![Figure 5.13 – Mini-arm with universal-joints](image)

![Figure 5.14 – Mini-arm with loose-joints](image)

The wires are inserted into flexible sheaths (Fig. 5.13, part 4) to make actuation of each joint independent. The working principle is similar to the wire bicycle break. The wire and wire sheath follow the same path along the mini-arm; the actuation is driven by stress difference between the wire and the sheath, so the actuation is not affected by changes in the mini-arm configuration.

Each mini-arm is actuated by two wires. If, for example, a mini-arm consists of three modules, the total numbers of wires and sheaths will be 6; six sheaths run on the first mini-arm, four on the second and two on the third. The sheaths lay along the cylindrical external surface of the mini-arms.

To allow the full rotation of each joint, some free bending sheath (Fig. 5.13, part 4), has to be left close to the joint. Each bending sheath describes a smooth arc, centred on the joint pivot; the path of the arcs describes a kind of sphere around each joint.

Despite the actuation, the universal joint mini-arm looks similar to the clutch $c$ of the
mini-arm with steered clutches (Fig. 5.12, part c). However the working principle is different. Both the mechanisms adopt a spool, to wind the actuating wire and an angular encoder. While the SMA spring is the clutch actuation element, the universal joint steel spring is the component that allows the backward motion of the wire. When the wire is not pulled, it sets the joint angular value to its original position. The first spool (Fig. 5.13, part 6) allows the rotation along the directrix of the cylinder frame; forward actuation is obtained by pulling the wire (Fig. 5.13, part 3), a spring (Fig. 5.13, part 7) supplies the backward motion. An encoder (Fig. 5.13, part 8) provides the joint angular feedback. The second spool (Fig. 5.13, part a), is also equipped with a spring (Fig. 5.13, part b) and an encoder (Fig. 5.13, part c), enables a rotation along an axis perpendicular to the previous one.

The last actuation to be described is obtained by a bevel gear transmission (Fig. 5.13, part 9). The universal-joint allows rotation in every direction (-180° to +180°, -140° to +140°). This solution is dexterous, compact and reliable. One of the main drawbacks is related to wire actuation. The diameter of the spheres formed by the wire sheaths defines the mini-arm maximum diameter; the spheres are built from compliant elements and so are partially compressible.

This characteristic has to be considered to design the trocar device. As mentioned before, the trocar diameter has to be as small as possible; it shall be slightly bigger than each module frame diameter to allow passing of both the module frame and the shrunk sheaths sphere.

5.3.4– Mini-arm with loose-jointed links

The loose-jointed links mini-arm (Fig. 5.14) is the result of the evolution of the family. The mini-arm with universal joints (Fig. 5.13) is formed by modules (Fig. 5.13, part 1)
that allow twisting around the mini-arm axis (Fig. 5.13, part 6) and bending (Fig. 5.13, part a). This design can be simplified. The mini-arm (Fig. 5.14) should be able to change direction to overcome obstacles bending (Fig. 5.14, part 2), but does not need to be twistable. The correct orientation of the surgical tool can be achieved by providing only the surgical tool, on the mini-arm tip, with a universal joint wrist (not shown in the Fig. 5.14). Each mini-arm module (Fig. 5.14, part 1), has a loose joint (Fig. 5.14, part 2). Like the clutch case (Fig. 5.11, part 1), each joint is actuated by three wires (Fig. 5.14, part 3); the number of wires shown in the Figure 5.14 is only 2 for clarity. Three kind of loose joints are proposed; spring, rubber and straw joint (Fig. 5.15, part a, b and c).

**Solution a.** Spring joint. The joint is a flexible steel spring. Inside the spring can be positioned a sphere. The sphere, when the actuating wires are tensioned, helps to give rigidity to the joint. It could be useful to use the spring joints without the inner sphere when the module frames are hollow pipes. In this case, the articulated mini-arm, formed by hollow components, result itself internally hollow. Hence, along the spring and pipes directrices, is possible to locate the control cables (Breedveld01).

**Solution b.** Rubber joint. This joint is formed by an hollow cylinder of rubber or gel. The rubber-gel joints can be securely attached to the plastic module frames; this technique is commonly used to produce modern toothbrushes.

**Solution c.** Straw joint. This joint is similar to the drink straw.
The three joints all allow a large degree of bending; the rubber joint and the spring joint are easier to realize, supplying passive restoring actions. As for the universal joint case (Fig. 5.13), each of the actuation wires (Fig. 5.14, part 3) runs into a flexible sheath (Fig. 5.14, part 4). All the sheaths are tied (Fig. 5.14, part 5) to the module frame (Fig. 5.14, part 1). The same considerations as for the universal-joints links mini-arm apply. The modules of figure 5.14 (Fig. 5.14, part 1) host a rubber joint (Fig. 5.14, part 2 and Fig. 5.15, part b). Actuation is done by wires (Fig. 5.14, part 3) to maximise the force/section ratio; a 0.3 mm diameter stainless steel monofilament allows a maximum load of 145 N.

The mini-arm shows a clean and robust design. The power supply is relocated to increase the overall system reliability; standard size motors are used instead of delicate micro-motors (used in solution 2). Resorting to loose joints reduces the requirement for MEMS. Clutches (solution 2), pulleys (solution 2 and 3) and bevel gears (solution 1 and 3) are not needed any more. The disposition of the actuation wires along the mini-arm (Fig. 5.14, part 4), is simplified (compared to solution 2 and 3). The parallel architecture of the actuation joints permits the use of the mini-arm even for critical operations, where accuracy is important. Usually, wire actuated surgery tools use a spring (like solution 3) to provide the backward movement; this limits tool miniaturisation and reliability (Podstędkowski02). To avoid this problem the solution replaces the three springs, which should be necessary for each joint, by a single deformable element embedded into the mini-arm. Encoders are positioned outside of the mini-arm (unlike solution 1, solution 2 with clutch c and solution 3) to minimise the overall size. Using such a design the diameter can be reduced to 6 or 5 mm: the universal joint on the tip of the mini-arm is the main hindrance for miniaturisation. The wire relocation limits the
number of modules to 4 or 5, granting proper compliance. The steel or rayon wires can be actuated for example by electric motors, SMA wires or electro-strictive polymer wires. Joint deformability has to be chosen carefully: high mini-arm stiffness enhances force-transmission performance, low stiffness allows passive compliance that in case of errors, helps to limit the damage to organs (Paap96).

While the axial and radial stiffness of a hollow gel cylinder (Fig. 5.15, part b) are similar, a steel spring (Fig. 5.15, part a) presents higher radial stiffness than axial stiffness. The main drawback of a spring is its radial lack of compressibility, and hence, low margins for transversal errors. The more homogeneous behaviour of the gel joint is more suitable to be used close to delicate organs. The main drawback of the loose-jointed links mini-arm however is its low modularity. Once the mini-arm is assembled, it is difficult to change the number of modules, as the sheaths for the actuation of the following modules run on the external surface of each module. The measure of wire stretch can give information about the contact between the mini-arm and some human body organs (i.e. simple force feedback).

Figure 5.16 summarizes the actuation principle that each mini-arm adopts; wire-driven mini-arm is actuated by a flexible shaft and clutches, mini-arm with self-powered modules adopts electric motors, mini-arm with universal-joints adopts either SMA spring clutches either electric motors, finally mini-arm with loose-joints is cable driven.
5.4 – The surgical instrument design methodology

After having deepened the knowledge about the requirements and the state of art of the MIS instruments, on the basis of the recalled discussion with filed experts about the preliminary conceptual solutions, the need of an appropriate design methodology is clear.

Due to the innovative character of the instrument and in order not to limit the design creativity, the resort to all kinds of mathematical models and virtual prototyping and testing tools seemed the right mean to adopt. In this way all the solutions may be evaluated and compared in terms of performances before the always costly physical prototyping. A simultaneous engineering approach, taking into account the mini components available on the market and specialising the modules and grippers functionalities was followed. From this bottom-up approach that draw to the definition of different modules and grippers stored in libraries open to new future solutions, a process of modules assembly synthesis in serial kinematic architecture has been applied using Genetic Algorithms oriented to the open chain architecture optimization with
reference to the given surgical procedure. For the selected architecture, a set of mathematical models has been written and set up to used at the control and supervision system level. This model based approach improves the instrument performances and control robustness. The dynamic model of the integrated surgical system, within the market environment, gives to the designer the possibility of evaluating the instrument characteristics before its realization. The overall scheme of the design process is shown in figure 5.17. The block circle near each design phase reports the thesis reference chapter. Design for human safety and body compatibility in terms of materials and instrument chain mobility have been considered as main issue.

Figure 5.17 – Design process
Minimally invasive heart surgery is very demanding for surgeons, even when using the existing robotic devices. One of the main reasons for this is the low dexterity of the instruments. Most of the existing devices use cables for actuation (chapter 3); this technology allows only limited intra-cavity mini-arm mobility and reduces its manipulability (dexterity). Chapter 6 introduces an innovative design methodology to increase the dexterity of the mini arms and thus allow MIS to be performed more easily.

A modular design concept for highly dexterous miniature mini-arms is described; the mechanical design of numerous actuation modules is presented, along with experimental validations of a module’s performances. The modules can be joined to form many MIS mini-arms. A preliminary design methodology, based on evolutionary algorithms (Sallé04a), has been developed to select the optimal module configuration for a given surgical procedure. This methodology allowed to select the mini-arm that best can perform coronary artery bypass grafting anastomosis. Some experiments have shown that the mechanical performance of the first module prototype is satisfying. A full size
prototype of the complete mini-arm has been produced, assembled and tested.

### 6.1 – Materials and methods

The proposed mini-arm design concept is based on modularity: an mini-arm holder, placed in the operating room, carries and moves the mini-arm. As the mini-arm is introduced through a trocar, only 4 DoF can be provided by the mini-arm holder. Any extra intra corporeal DoF must be provided by the mini-arm.

Increasing the number of DoF of the mini-arm, manipulability and thus dexterity are enhanced, but stiffness and accuracy are lowered.

Designing a dexterous mini-arm for MIS thus means designing an mini-arm carrying an high number of DoF. Cable based actuation, due to the size of the pulleys and the number of cables that must run through the joints, limits the number of distal DoFs.

The proposed design adopts independent, electrically powered actuation modules that, mounted as a serial chain, form the dexterous mini-arm. A needle holder is then mounted on the last actuation module to allow needle holding and releasing.

A standard interface and a serial bus provide the mechanical, power and signal link between the modules. The actuators are placed inside each module to enhance the system modularity. Two miniature actuators has been considered; brushless micro-motors and shape memory alloys (SMA) wires.

It is convenient to provide each module with as many DoF as possible to increase the mini-arm's dexterity; modules having one or two DoF have thus been designed. This modular design concept allows the creation of redundant mini-arms. The redundancy must be controlled and can be used to locally optimize the dexterity of the mini-arm, to avoid the organs and allow the mini-arm to be tolerant to joint range or joint torque
Such mini-arm could be used to carry out surgical procedures with increased ease for the surgeons and even access areas that could not be accessed before, thus allowing for new procedures to be performed in a minimally invasive way. However, many constraints must be taken into account when designing such a MIS mini-arm.

### 6.2 – Design constraints

The design constraints are imposed by the MIS theatre: the mini-arms are inserted in the body through port-access, also called trocars. The maximum size of these trocars for thoracic surgery is 10 mm, imposing the mini-arm modules to be cylindrical with a maximum outside diameter of 10 mm. This constraint on the module size has a great impact on the constraints of actuators: they must be small, and hence have low power.

There is no constraint on the complete mini-arm length: one can add as many modules as he wants, as long as he can control the mini-arm and avoid the organs. However, it is straightforward that a mini-arm having short modules will have higher dexterity than an mini-arm having the same kinematic chain but longer modules.

As the modular mini-arm is used to perform surgery, critical joint speed and torque constraints apply, as opposed to endoscopes that only have to sustain their weight and move slowly to a different location.

These joint power constraints depend on the procedure to be carried out. As CABG anastomosis is concerned, and as no experimental data could be found, a surgical gesture recording platform has been developed and the CABG anastomosis procedure has been modeled (Sallé04b). Figure 6.1 shows the CABG principle: a graft derives the blood flow downstream the lesion on the coronary artery. The suturing of the graft on
the coronary artery is called anastomosis.

From the experiments performed ex-vivo by surgeons, the anastomosis gesture main features can be extracted: elliptic motion around the artery’s incision, 20 perforation points –1 mm step– produced by a small translation combined with a rotation of 120° of the mini-arm, perforation force of 0.3 N, forces to tie the thread on each point of about 1.0 N. From literature, the clamping force needed to hold the needle ranges from 5 to 40 N (Sallé04c).

This data is used to generate a trajectory that the mini-arms has to follow. It thus defines indirect design constraints, that will be dealt with by a simulation of the surgical task.

Safety is also a major constraint in the design of systems for surgery: if, for any reason, the tele-operation fails, the surgeon must be able to remove quickly the mini-arms and continue the operation using more classical instruments. Fast retrieval of the mini-arm is then a key feature. This imposes the mini-arm to be easily removed by the entry-point.
Thus cylindrical modules should have rather small length. The proposed modular design concept complies with this constraint.

Another safety issue is that the mini-arm should not damage the surrounding tissues and organs. The first barrier for this is to put contact sensors on the mini-arm and implement obstacle avoidance in its control. Meaning the necessity to fit angular sensors in the design of the modules, that allow a precise position control and thus accuracy in the movement.

The modules should also have low intrinsic power, so that even if the mini-arm becomes uncontrolled and gets in contact with organs, its low power could not damage the contacted organ. Both these aspects are implemented with the proposed design concept, allowing it to be rather safe.

However, low module power, and high number of serial chained modules are antagonist objectives. The design of the complete mini-arm must thus be a compromise among available motion, joint torque, range limitations and dexterity.

**6.3 – Components selection**

The illustrated constraints limit the range of commercial and custom components that can be used for bulk material, actuation, transmission and sensing (Fig. 6.2).

Section 6.3 introduces some of the available components that can be used for the design of a self powered mini-arm.
6.3.1 – Bulk material

The choice of the material depends on the mechanical requirements and on the design strategy. The forces that is necessary to exert during the surgical operation are relatively low; for this reason, the frame of each module is made by plastic. The following materials has been compared; nylon (EETALON 66SAMU and 66GF-30), PEEK (Poly-Ether-Ether-Ketone), polypropylene and Torlon (Poly-Amide-Imide). Peek and Torlon has been selected as best candidates. Final choice has fallen on Peek; density 1.4 g/cc, tensional modulus 5700 MPa, melting point 180° etc. The mini-arm, made by Peek (Appendix A), under 10 N axial load and 3 N bending load suffers negligible deformations.

6.3.2 – Actuation

The modules actuation can be performed by cables, SMA wires, SMA springs clutches, miniature motors etc. (Cepolina03). A general survey on innovative actuation technologies is given in chapter 4.

Miniature motor actuation is an interesting compromise solution: despite it provides low
torque, it allows the modules to be highly independent and accurately controlled.

Faulhaber offers a range of motors from Ø 1.9 mm (breakdown torque 7.5 μNm).

Smoovy provides motors ranging from 3 to 5 mm. The Smoovy 3 mm coupled with a 1:125 planetary gearbox, gives a torque of 0.88 mNm (Appendix A).

The Penn State University developed a piezoelectric motor, Ø 1.8 mm and 4 mm long, having high power to volume ratio. The performance of this motor sounds really attractive; the motor provides high torque at low speed and so doesn’t need gearbox. However, this motor is not yet commercially available.

If higher ratios gearboxes are needed, Micromotion sells miniature harmonic drive gearboxes; diameter is 8 mm reduction is 1:512 and 1:1024.

### 6.3.3 – Transmission

The axis of rotation of a module may have generally any inclination. Two basic configurations are examined; axis parallel or perpendicular to the module axis. Each module has a cylindrical shape. Because of their size, electric motors can only be placed along the axis of the modules, 90° transmission is thus necessary. There are different mechanical connections that allow a 90° torque transmission: soft link tubing, pulleys, flexible joints, gears and Hooke’s joints.

Didel sells plastic molded face gears (module 0.3). However these gears are too big to fit in our specific application. Face gears can’t be machined in metal, they must be plastic molded, and thus produced in big series. They are thus incompatible with prototyping.

Graupner Modellbau, Germany, sells Hooke’s joints and miniature flexible joints.

Rapid Electronics Ltd., UK, sells a soft silicone polymer tube which can be used as a flexible coupling. Both the last two coupling are not suitable for high accuracy.
Design of modular end-effectors

Thanks to precision machining, miniature transmissions such as follower driver, miter gears, worm gears, helical gears and face gears can be produced. The gears can have, for example a module up to 0.15 or smaller; gears having an external diameter smaller than 10 mm and a module smaller than 0.3 usually need to be custom made.

6.3.4 – Sensors

Different kind of miniature angular sensors: inductive, magnetic, capacitive, optic and resistive exist (Fig. 6.3).

<table>
<thead>
<tr>
<th>Principle</th>
<th>Company</th>
<th>Description</th>
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<tbody>
<tr>
<td>Inductive</td>
<td>Posic S.A.</td>
<td>Custom based on PO1210</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Philips</td>
<td>KM110B/2</td>
</tr>
<tr>
<td></td>
<td>Sentron</td>
<td>2 SA-10</td>
</tr>
<tr>
<td></td>
<td>Austrian Microsystems</td>
<td>AS5020-E</td>
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<td></td>
<td>Honeywell</td>
<td>HMC 1501</td>
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<td>Infineon</td>
<td>TLE-4906</td>
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<td></td>
<td>Allegro</td>
<td>3046, 3056 and 3058</td>
</tr>
<tr>
<td></td>
<td>Bell</td>
<td>BH-205, BH-208</td>
</tr>
<tr>
<td>Capacitive</td>
<td>Aoip</td>
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<td>Optic</td>
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<td></td>
<td>Jameco</td>
<td>Flex sensor FLX-01</td>
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<td></td>
<td>Eurofarad</td>
<td>Custom</td>
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Orbital Technologies Corporation offers a 5 mm diameter optical encoder. Each Orbital sensor requires an independent optical cable to transfer the signal to the sensor electronics. It is however not possible to place the Orbital sensor in all the modules: as the cumbersome electronics must be placed outside the mini-arm, the optical fibers of each sensor should run through all the mini-arm’s modules. Which is impossible, due to the 10 mm diameter constraint on the mini-arm.

Resistive or capacitive trimmer can be used as angular sensors, but for such small
diameters, their resolution and range are too low.

Inertial measurement units or gyroscopes could be made small (ADXRS300 from Analog Devices Inc: 7x7x3 mm). However, drift and position errors are major problems of such systems.

Hall sensors can sense magnetic fields along one direction. Coupling two perpendicular hall sensors, such as done in the Sentron 2SA-10 sensor (Appendix A), allows to sense a rotating field in a plane. Sentron 2SA-10 is a non contact angular sensor able to detect the absolute position of a rotating magnet with an accuracy of less than 0.2 deg.

Vision sensor is mounted as the end effector of one of the mini-arms. A mini camera from the market may be used. Visual information are sent to the visual interface on the surgeon console for teleoperation. Tactile sensors are foreseen to avoid possible impact with the patient body improving the mini-arm safety. Vision and tactile sensors are not implemented into the actual physical prototype.

6.4 – Modules overview

More than twenty-five modules has been designed following the strategy detailed in chapter 2 and using the commercial components of chapter 4. Each module has one or two DoF (Fig. 6.4); in this scheme, the arrows show the direction of the actuated DoF.

![Figure 6.4 – Classification of modules](image.png)
Figure 6.5 gives an overall view of a selection of the designed modules. The modules are position controlled; a main frame holds actuation, transmission and sensing components. The components forming a module are assembled using screws, weldings and glue; modules are joined each over by screws. Appendix B reports the technical drawings used for the machining and assembly of the mini-arm. The Ø 10 mm frames of the modules are machined from PEEK by a 5 axis machine tool. There are two types of modules: body modules and end effectors. A selection of the modules is reported in the sections 6.5 and 6.6.

6.5 – Body modules

Different mechanical solutions have been investigated for the actuation of the mini-arm (Fig. 6.5). The body modules are classified into two subcategories 1 DoF modules (Section 6.5.1) and 2 DoF modules (Section 6.5.2).

6.5.1 – One DoF modules

While electric motors can power both kind of modules, SMA actuators, due to their low bandwidth, are suitable mainly for clamp actuation. Among brushless micro-motors, the best trade-off between size and power is the Smoovy 3 mm motor: it is thus used in most of the designs (Appendix A).

Bending module 1A

The module has 1 DoF perpendicular to the axis of the module. Its motion range is 150° (Fig. 6.6). The lower and the upper frame are made of Peek (Fig. 6.6, part 1 and 2). The speed of the Smoovy motor (Fig. 6.6, part 5) is reduced first by its planetary gearbox (reduction 1:125), then by a coupling between a spur gear and a face gear (part 6 and 7, reduction 0.625). The lower part of the face gear is cut to transmit the torque to
Figure 6.5 – Classification of modules
Design of modular end-effectors

the upper frame (Fig. 6.6, part 9 and 10). A miniature screw (Fig. 6.6, part 8) links the face gear with a magnet (Fig. 6.6, part 11).

Two ball bearings, assembled with interference, reduce the friction between the two rotating parts (Fig. 6.6, part 12 and 15); the smaller bearing, from WES-Technik GmbH, measures 1 mm inner diameter, 3 mm outer diameter, 1 mm width. The Sentron 2SA-10 sensor (Fig. 6.6, part 13 and 14), fixed on the lower part of the module, reads the angular position of a magnet rotating with the upper part of the module. To allow an easy modules coupling, each module has at its extremities the same mechanical interface (Fig. 6.6, part 3 and 4).

The design is compact; the face gear and the sensor positions are studied to keep the overall length of the module as short as possible. There are however three main drawbacks: the face gear is difficult to machine, the torque of the module is low and the upper and lower parts of the frames are too weak.

Figure 6.6 – Bending module 1.A
This solution (Fig. 6.7), should improve the previous design; now the assembly procedure is easier, the sensor (one axis hall sensor) is placed lower (Fig. 6.7, part 9) to make the lower frame (Fig. 6.7, part 1) stronger. A plate (Fig. 6.7, part 10) secures the motor to the lower frame. The gear transmission (Fig. 6.7, part 6 and 7) is the same as in solution 1.A. Both the left and the right side of the lower frame host ball bearings (Fig. 6.7, part 12) and the left side (Fig. 6.7, part 11) can be dismounted for the module’s assembly. The sensor reads the position of a multipole magnet ring (Fig. 6.7, part 8) mounted on the upper frame (Fig. 6.7, part 2). Two different sensors can be used: the Sentron 2 SA-10 or the Bell BH-208. In this configuration, the Sentron sensor records incremental positions, in opposition to solution 1.A where it detects absolute angles. Multipole magnets are costly, difficult to machine and mount. Moreover, the position accuracy depends only on the number of poles in the magnet. This number is limited by the technology used to produce the magnets, leading to low accuracy and resolution. This solution also suffers low torque.
**Bending module 1.C**

As for the previous solutions, a 3 mm Smoovy motor with 1:125 gearbox drives the module (Fig 6.8, part 4). It is advisable to provide the modules with slow speed and relatively high torque (Peirs00). The worm and gear coupling (Fig 6.8, part 5 and 6) is the transmission that best fits this task, as it is compact and can have high reduction ratios. Smoovy motors can hold only 0.1 N of axial and radial loads. To avoid force transmission between the worm and the motor, its shaft is inserted in a holed part (Fig 6.8, part 10), secured on the lower frame (Fig 6.8, part 1). It guaranties good shaft alignment and absorbs the radial forces generated by the gears. The module is 24 mm long.

![Bending module 1.C](image)

**Figure 6.8 – Bending module 1.C**

A 2SA-10 Sentron sensor (Fig 6.8, part 8 and 9) measures the angular position of a magnet (Fig 6.8, part 7) glued on the gear, itself mounted on higher frame (Fig 6.8, part 2). Two M1 screws (Fig 6.8, part 3) secure the upper frame with the following module.
The module payload can be further enhanced choosing a not reversible worm and gear transmission for the modules actuation.

The non reversibility is used to propagate the forces from the mini-arm holder to the tip of the mini-arm. This possibility is used only when the actuation modules don’t have enough torque to produce the desired motion. They are then blocked in their current position and used as a stiff transmission.

**Axial module 2.A**

The upper frame (Fig. 6.9, part 2 and 4) can rotate with respect to the lower frame (Fig. 6.9, part 1); two bearings (Fig. 6.9, part 12 and 13) decrease the friction between the two parts. The bearing, separated by a spacer (Fig. 6.9, part 15), are secured to the lower frame by a collar (Fig. 6.9, part 3). Four holes are made around the circumference to insert screws: two screws fix the collar to the lower frame (Fig. 6.9, part 14) while the others are inserted as a mechanical link between this module and the previous one.
Four other screws (Fig. 6.9, part 16) link the upper frame to the spacer. The gear (Fig. 6.9, part 6), mounted on the motor gearbox (Fig. 6.9, part 5), has two tasks; it drives a crown (Fig. 6.9, part 11) and a face gear (Fig. 6.9, part 7). The crown is part of the upper frame of the module. Like for the module 1.A, the face gear changes the orientation of a magnet (Fig. 6.9, part 8) whose absolute angular position is measured by the angular sensor (Fig. 6.9, part 9 and 10).

The main drawbacks of this design are: the module provides low torque, the assembly is complex, the crown gear and the face gears are difficult to machine.

**Axial module 2.B**

A further study has been performed to simplify the design of module 2.A. In the previous module, the face gear was very close to the motor gearbox. High precision assembly was thus required. Solution 2.B has no face gear (Fig. 6.10); the gear (Fig. 6.10, part 6) that rotates the crown (Fig. 6.10, part 7) is magnetic.

![Figure 6.10 – Axial module 2.B](image-url)
The change in the magnetic field measured by the hall sensor BH-205 from Bell (Fig. 6.10, part 8) allows to detect the crown’s teeth, and thus the angular position of the module. The sensor thickness is only 0.4 mm. The two ball bearings of solution 2.A have been replaced by two friction bearing (Fig. 6.10, part 9 and 10) directly part of the lower frame (Fig. 6.10, part 1). Once the motor (Fig. 6.10, part 5) is inserted into the lower frame, its position is adjusted by a plate secured by two screws (Fig. 6.10, part 12). The upper frame is made of two elements (Fig. 6.10, part 7 and 2) linked by screws (Fig. 6.10, part 13). As usual at the module extremities is placed the mechanical interface (Fig. 6.10, part 3 and 4).

The main drawbacks of the module are: the magnetic gear is difficult to machine, the sensor is costly and not absolute, the torque is low.

**Axial module 2.C**

The two previous axial modules present some common drawbacks; machining of the crown is not easy, assembly is relatively complex and torque is low. The present solution tries to solve these problems (Fig. 6.11). The crown gear transmission can be eliminated; the upper frame (Fig. 6.11, part 1) is joined directly to the shaft (Fig. 6.11, part 3) of the gearbox (Fig. 6.11, part 2) of a bigger motor. Smoovy 5 mm brushless motor with reduction 1:125 has enough torque to drive the needle in the arteries. The rotating part of the module is made of a stack of three elements: the upper frame, the sensor and the mechanical interface (Fig. 6.11, part 7). Two screws, not shown in the figure, join these elements. A magnet ring (Fig. 6.11, part 4) is glued on the gearbox. The Sentron sensor (Fig. 6.11, part 5 and 6), detects the magnet position. Like the other axial modules (solutions 2.A and 2.B), the sensor position enables to record several full rotations of the module. The link between the gearbox shaft and the upper frame (Fig. 6.11, part 8)
is weak: the space between the magnet and the shaft is limited. The main drawback of this module is its length.

6.5.2 – Two DoF modules

Two DoF modules are intrinsically more complex than 1 DoF modules and generally shorter than two 1 DoF modules in series: the mechanical connection interface necessary to link two 1 DoF modules can be avoided. Each DoF is formed by a motor, its gearbox, a transmission and a position sensor. Ideally, the shortest possible 2 DoF module has these components perfectly overlapped. All the 2 DoF designed use the Smoovy 3 mm motor with the 1:125 gearbox.

Differential module 3.A

The differential wrist is a classic actuation (Fig. 6.12). The module is made of three main elements: a lower frame (Fig. 6.12, part 1), an upper frame (Fig. 6.12, part 2) and the
upper mechanical joint (Fig. 6.12, part 3). Each of the two aligned motors (Fig. 6.12, part 4 and 5) powers a face gear (Fig. 6.12, part 6 and 7); the gear ratio is 8:24. The shafts of the face gears rotate inside an element (Fig. 6.12, part 8) secured by two screws to the lower frame. Both the face gears drive an additional flat gear (Fig. 6.12, part 9). The module is about 26 mm long; the bending range is about 125° and axially it can perform several rotations.

The Ø 10 mm constraint on the mini-arm diameter does not allow to fit any sensor in this design. The face gears must be plastic molded and thus produced in big quantities and could not be replaced by conic gears as they have to interact with 2 other gears having different diameters.

![Figure 6.12 – Two DoF module 3.A](image)
Module 1.C (Fig 6.8), thanks to its worm and gear transmission, is the bending module that produces the highest torque among the proposed designs. It is possible to create a 2 DoF module composed by the fusion of two 1.C modules, each mounted on one extremity of the module (Fig. 6.13). Two versions of this module are designed: the axes of the joints can be parallel or perpendicular. The motor (together with its gear box) is longer than the sensor electronic board. The parallel axes module is 5 mm shorter than the perpendicular joints module: in the first case the 1 DoF modules are approached until the sensor cards are about in contact (Fig. 6.13, part 1 and 2), in the second case, each sensor card touches the motors before to touch the other sensor card (Fig. 6.13, part 3 and 4). The module (frame, motors, bearings, screws, gears, sensors, magnets) weights about 6 grams and is 36 mm long.

**Figure 6.13 – Two DoF module 3.B**
**Universal module 3.C**

The module is a sort of spherical joint (Fig. 6.14): the design 1.C (Fig. 6.8) provides bending, while an evolution of the module 2.B (Fig. 6.10) drives the axial rotation. The shaft of the motor gearbox drives the higher frame (Fig. 6.14, part 2) thanks to a crown-gear transmission (Fig. 6.14, part 1 and 2). The crown is directly cut inside the upper frame. A plate (Fig. 6.14, part 3) places the motor in the right position and supports the motor shaft. The angular sensor (Fig. 6.14, part 7) detects its position with respect to the circular magnet (Fig. 6.14, part 5). Four screws (Fig. 6.14, part 4) link the upper frame with the lower frame, forming a sort of bearing: the tip of the screws can slide between the plate and the upper frame and allow the axial rotation of the module. To increase the torque of the rotational joint, the number of teeth of the crown has been maximized. The upper part of the module is made of four elements: the upper frame (Fig. 6.14, part 4), a connection element (Fig. 6.14, part 6), the sensor (Fig. 6.14, part 7)
Design of modular end-effectors

and the mechanical interface (Fig. 6.14, part 8). Two screws parallel to the module axis link the mechanical interface with the sensor and the connection element. Two screws, perpendicular to the axis module (not shown in the figure), link the mechanical interface with the upper frame.

### 6.6 – End effectors modules

The mini-arm needs a wide set of end effectors to operate. Some examples of tools are now briefly described; scalpel (Section 6.6.1), syringe (Section 6.6.2), sewing rig (Section 6.6.3), needle holders (from Section 6.6.4 to Section 6.6.8). The design of a gripper short and having high clamping force is crucial; Section 6.7 reports the detail design of two needle holders.

#### 6.6.1 – Scalpel module 4.A

A given surgical procedure can be performed using at least three different techniques. The task, for example, can be to perform a short straight incision on the tissue of an organ inside the human body. In the traditional way (open surgery), the surgeon, having a scalpel in his hand, performs the cut, moving both his wrist and his arm. In the current MIS (anthropomorphic robotics), the scalpel is the end effector of a miniature robotic arm. The mini-arm and his wrist replicate the traditional movements of the surgeon’s arm and wrist. In the prospective MIS (instrumental robotics), the robotic mini-arm end effector is an active scalpel. This scalpel is a self-powered module; by means for instance of a miniature motor (located inside the module), the scalpel blade, during the cutting phase, is driven along a straight line. The mini-arm and its wrist place the active scalpel in contact with the tissue organ. During the cutting phase, the mini-arm control guarantees that there is no relative movement between the active scalpel
and the organ. The cutting is fully performed by the self-powered scalpel blade, under the supervision of the surgeon.

6.6.2 – Syringe module 5.A

The syringe is a comparatively traditional tool, (Fig. 6.15), for drug delivering. We distinguish four parts: the frame, the plunger, the body and the actuator; the body, located inside the frame, can slide 3 mm along it, assuming the two positions: retracted (Fig. 15, part a) and extended (Fig. 15, part b). The circles of the figures a and b show the location of the wounding ends (needle pin or knife tip), respectively in the retracted and in the elongated position.

The syringe tool is formed by three components; the main frame, the syringe back part, the syringe body and the actuation device. The syringe body is positioned into the syringe frame and can slide about 3 mm along it; thanks to this gap, it can assume two positions, retracted and elongated. The actuation device has the task to push the syringe back part. During the insertion phase the syringe body is full of liquid and the syringe back is about all out of the syringe body. During this phase the syringe body is in the retracted position: while the syringe body is in this position, the frame covers the needle tip to avoid accidental picks. When the tool has reached the operating position, the actuator pulls the syringe back part. Initially the actuator push moves forward the syringe body (from retracted position to elongated position), inserting into the flesh the needle. Then the actuator push is used to insert the liquid into the patient body. Once the liquid is injected, the actuator positions the syringe body in the retracted position for a safe syringe retrieval.
The actuation device pushes the plunger. During insertion, the body is full of liquid, the plunger is retracted and the frame covers the needle pin to avoid accidental picks. When the tool has reached the operating position, the actuator presses the plunger. Initially, actuation push moves the body forward to the elongated position, inserting the needle into the flesh; then it inserts the liquid into the patient body. Once the liquid is injected the actuator brings back the body in the retracted position, for safe syringe removal. The scalpel tool has the same working principle as the syringe; the blade is extracted and used only when the tool is secured in the work stand.

6.6.3 – Sewing rig module 6.A

Today sewing is one of the most difficult inner-body tasks; the surgeon, using two grippers, needle and wire, ties step by step new knots, in remote-operation. In much the same way as the sewing machine was invented to replace the repetitive movements of the human hands. Similarly the automation of surgical seams could give advantages: sewing time could be decreased and standard quality achieved; moreover to lower the impact, instead of two hands, a single device should reliably stitch up with task-specific motion (Stringer01).

A miniaturised sewing rig has been conceived that is able to stitch in full autonomy (Fig. 6.16) once duly located on the cut to sew. This tool includes four parts: a frame, a
suction device, a motorized helical hook and a sewing wire. The helical hook is internally hollow to host the sewing wire; this presents a knot on its extremity close to the hook tip. The sewing procedure requires the following steps:

- the mini-arm positions the sewing tool on the wound;
- the suction device keeps the tool in firm contact with the flesh;
- the helical hook moves forward, rotating as it goes, and creates holes inside both borders of the wound. The sewing wire, positioned inside the hook, moves forward as well;
- a small hinge, linked to the sewing rig frame, extracts from the hook tip the sewing wire knot and holds it firmly;
- the helical hook rotates backward, leaving on its path the naked sewing wire; during this phase, a stretching system keeps the sewing wire under tension;
- a knot is created on the other side of the sewing wire, to complete the sew.

Once a seam is over, the rig is ready to start darning again; the sewing wire is stored in the rig around a small spool. The procedure allows several changes; it is possible for example, to create knots by melting down a part of the wire by heating it electrically. An internally holed nail is driven, for example by a small DC motor.
6.6.4 – Needle holders: hydraulic power - module 7.A

The needle holder is one of the most important end effectors necessary to accomplish suturing tasks; the requirements for this gripper are: external diameter of 10 mm, a gripping force higher than 4 N and close to 40 N, an opening angle of at least 45° and a length as short as possible. Gripper actuation can be performed by hydraulic power, cables (powered by actuators located outside the patient body), shape memory alloys (SMA) wires, SMA springs, clutches, miniature motors etc. (Stevens98).

In the case of cable based actuation, the cables run trough all the mini-arms modules; each module hosts a segment of the gripper cables. This solution solution, despite it is widely used in the surgical field (Cavusuglu01, Cavusuglu99), has been rejected for modularity reasons. It is difficult to embed the cables inside a poli-articulated mini-arm; if each module is independently actuated, assembly and reliability are improved. As additional drawback, the gripper cable actuation generates forces along the proximal modules; these forces are counter-balanced by the proximal modules frames and actuators. Therefore, depending on the mini-arm stiffness and actuators power, cable actuation can affect the whole mini-arm control.

Miniature electric motors can be easily controlled but have a low power/volume ratio and need gearboxes; the outside diameter of the mini-arm limits the actuators size and hence the module power. SMA actuation is easy to actuate, gives an high power/volume ratio but is difficult to control due to the material hysteresis; the actuation bandwidth is limited by the SMA cooling time.

As the gripper should reach only two states - open and closed position - most of the proposed modules are actuated with SMA. SMA can be made in a lot of various shapes: wires, springs, cylinder etc. However as cooling time is the key parameter for the design
of SMA actuated mechanisms, cylinders cannot be used. SMA springs are used for traction but are long and have medium power. Torsion springs produce very low torque. So SMA wires seem to be the best solution for the design of a surgical gripper.

When heated by electric current, the SMA material shifts to austenite state and, thanks to the memory effect, the wire shortens. As response time is driven by the wire temperature, the time necessary to cool the wire under natural convection is the main problem. Cooling time under natural convection is directly related to the exchange surface area between the wire and air; to speed up the actuation, this surface should be increased replacing a single big diameter SMA wire with several small diameter SMA wires. Due to the limited available space, none of the gripper modules includes a sensor to control the clamp angle. A rough idea about this measure can be derived measuring the electric resistance of the SMA; anyway, because the full operation is supervised by a laparoscopic camera, the surgeon can retrieve information about the clamp position, directly from the camera’s images.

The main specifications for the gripper are: 40 N grasping force, 10 mm external diameter, about 25 mm length, possibility to work in an humid environment, reliability.

Three types of actuators have been considered: electric motors, hydraulic pistons and shape memory alloys (SMA).

We propose a basic scheme for the hydraulic actuation. The fluid enters from a door (Fig. 17, part 1) into a chamber (Fig. 17, part 2). Inside the chamber slides a piston (Fig. 17, part 4); an o-ring avoids the fluid leak (Fig. 17, part 3). The piston drives a shaft on which is linked a pin (Fig. 17, part 6). The pin moves both the jaws (Fig. 17, part 7). A spring (Fig. 17, part 5) produces the closure motion. As recalled before, fluid feeding complicates the mini-arm architecture. A similar scheme is proposed by Peirs (Peirs98).
6.6.5 – Needle holders: electric motors

Two motors actuation – module 8.A

Initially it has been chosen to drive the gripper with classic electric motors from Faulhaber. The motors (Fig. 18, part 1) are coupled with planetary gearboxes (Fig. 18, part 2) to increase the torque. Conic gears (Fig. 18, part 3) transfer the motion to the jaws (Fig. 18, part 4). The actuation of both the jaws has the same schema. The two conic gears, mounted on the shaft, are idle; while the shaft is fixed, the gears can rotate.
The jaws can be independently actuated; this embodiment allows the jaws to close along the axis of the device, or at any other angular position. A similar independent jaws closure can be found in the patent from Intuitive (patent WO0059384, ComputerM04). This solution has been discarded because the motion is reversible; a force applied on the jaws can rotate the motor and loose the grasp. Furthermore the machining of the $\varnothing$ 3 mm conic gear is difficult, and the forces generated by this kind of motor are not sufficient for a firm grasp.

**One motor actuation 1 – module 8.B**

A second motorized gripper is now illustrated. The nut is coupled with two jaws. The module (Fig. 6.19) is actuated by a 5 mm diameter Faulhaber motor coupled with an harmonic drive 1:500 gearbox – Micromotion GmbH company – (Fig. 6.19, part 2). The gripper frame (Fig. 6.19, part 1) is fixed on the gearbox. The gripper mini-arms, powered by a worm and gear transmission (Fig. 6.19, part 3 and 4), are optimised to supply the highest couple; each mini-arm lever (Fig. 6.19, part 5) is 10 mm long. The module provides up to 55 N of gripping force; the gripper (Fig. 6.19, part 6), has an opening spam of 56°. The step of the worm can be further reduced to increase the transmission rate. At the moment there is no sensor inside the clamps; the surgeon, from the endoscopic images closes the feedback loop. This solution presents the advantage to be not reversible. The main drawback of the module is its length (37 mm) that drastically limits the length available for the other modules used for motion.
Design of modular end-effectors

One motor actuation 2 – module 8.C

The length of the module 8.B can be decreased replacing the motor with a smaller one; from 5 mm to 3 mm diameter (motor always from Smoovy-Faulhaber). The motor is coupled with a three stages planetary gearbox 1:125. Like in the previous solution, a screw nut transmission gives power to the gripper jaws (Fig. 6.20). Part A and part B offer a detail view of the clamp open and closed position. This module is compact (length 24 mm) but delivers a limited clamping force (4 N).

The gripper's module length/power are critical for the completion of the task; while the module 8.B seems too long to allow a natural movement of the surgery mini-arm, the module 8.C doesn’t provide enough force to safely grasp the needle.

Figure 6.19 – Gripper actuated by electric motors II
Grippers actuated by electric motors seem not suitable for MIS. SMA and in particular NiTiNol have a typical recovery strain of 4% and can be easily integrated inside miniature grippers; this solution is compact, exerts high forces and has a relatively simple architecture. Some designs adopting SMA are now proposed.

The two ways memory shape effect (TWMSE) presents interesting advantages; the material is trained to “remember” two different geometries, each recalled at a different temperature (Huang01). Figure 6.21 shows the working principle of a gripper actuated by two identical bars of SMA. Each bar can assume one of the two shapes: straight (Fig. 6.21, part 1) or curved (Fig. 6.21, part 2).
Design of modular end-effectors

There are two main drawbacks using the TWMSE; the forces and the maximum number of cycles are limited compared to one way SMA. Even a light overheating of the two ways SMA is enough to loose the two remembered geometries (Johnson04). It has been therefore chosen to use only the one way memory shape effect (OWMSE) of the SMA.

6.6.7 – Needle holders: SMA springs - module 10.A

Figure 6.22 shows a gripper powered by a popular SMA linear transducer; a SMA spring provides forward motion, backward movement is given by a steel spring.

![Figure 6.22 – SMA spring gripper](image)

A rich literature describes this kind of linear actuator (Stevens98). For our specific problem, 40 N gripping force, the size of the SMA spring results too big to be embedded inside the mini-arm, moreover the cooling time of such a NiTiNol spring is too long for the surgical procedures.

6.6.8 – Needle holders: SMA wires

This solution adopts SMA wires; for a shortening from 3% to 5% the life cycle is $10^5$
SMA wires can be heated, for example, by electric current. When cooled, the wires must be pulled to restore their initial length. A series of SMA wires (Fig. 6.23, part 1) opens the jaw of the gripper (Fig. 6.23, part 2); the closure is provided by a steel spring (Fig. 6.23, part 3).

The SMA clamp has only one jaw instead of two, this choice simplifies the clamp design and enhances the grasping precision. The grasping procedure is split in two parts; first the surgeon brings the fixed jaw close to the needle, then the rotating jaw is closed. Vice versa, in the case of two mobile jaws, if it is asked the needle not to move during the grasping procedure, the needle has to be centred respect to the axis of the gripper.

The shortening of the wires is only 4%; several pulleys (Fig. 6.23, part 4) are used to obtain simultaneously a wire length sufficient for the jaw opening and a compact gripper. The wires are placed in parallel to enhance the gripper bandwidth and the grasping force.
Further considerations led to change slightly the original design. Solution 11.A uses a steel spring, like a clothes peg, to close the gripper: SMA wires provide for the clamp opening. It has been chosen to invert the steel spring and the SMA wire functions for the following reason; while the steel spring for the jaw closure (solution 11.A) is big to exert the closure force, the spring used for opening is small because it has only the task to stretch SMA wires. The main drawback of this embodiment is that a prolonged closure of the clamp can generate the overheating of the wires and then the heating of the whole clamp.

![Figure 6.24 – Gripper with SMA wire for closure](image)

This effect increases the cooling time of the wires lowering the gripper opening speed. Figure 6.24 shows the final version of the gripper; the fixed jaw is part of the frame, in the frame are inserted the rods that support the wire pulleys.

**Parallel SMA wires 1 – module 11C**

One possibility to reduce the overall length of the last two modules of the MIS mini-arm is to combine them: the module (Fig. 6.25) has 2 DoF: self-rotation and gripper.
Combining a 2 DoF actuation module and a parallel gripper is not feasible due to size limitations in the module’s diameter.

An electric motor, located in the lower part of the module, provides the wrist rotation; the segment A (27 mm long) can rotate respect to segment B (13 mm long). The clamp (Fig. 6.25, part 6, 7) is actuated by eight SMA wires (Fig. 6.25, part 5) running along the external surface of the module as for the parallel SMA gripper (Fig. 6.26). The positioning and fastening of the wires along the external surface is not easy. The segment A is composed by two parts; its upper part (Fig. 6.25, part C) hosts the mechanics for the clamp movement, its lower part hosts internally the motor of the wrist and externally the SMA wires of the gripper.

The gripper of module 8.C has to be adapted to be integrated into this module (Fig. 6.25, part c); two screws link part C with the rest of the module; the first element (Fig. 6.25, part 1) is placed around the motor, the second (Fig. 6.25, part 2) sustains the gripper’s jaws rotation axis (Fig. 6.25, parts 6,7 and 8). The SMA wires are fastened to the motion disk (Fig. 6.25, parts 3,4). Module 8.C has shown that the electric motors are too long and cumbersome to power clamps; for financial reasons, the Penn State piezoelectric motor has been excluded. The wires along the external surface cannot be easily replaced. SMA wires have rather low bandwidth, due to the cooling phase; to increase this bandwidth while maintaining the same load capacity, a single wire has been replaced with several wires of smaller diameter.
This module is compact but presents some drawbacks: machining and fastening are complex. The overall length of the module, while reduced in comparison to the use of two separate modules, is still important and is not compatible with heart surgery. Moreover, in case of clamp failure, it would be necessary to replace the whole module. As additional drawback the control embedded in the module needs to drive, at the same time, two different types of actuators; an electric motor and SMA wires.

**Parallel SMA wires 2 – module 11.D**

Module 11.D is a stand alone SMA clamp (Fig. 6.26). The axial translation of a disk drives a pin that controls the opening and closing of the gripper. When the wires are cold (long), a spring placed in the module, pushes against the disk, keeping the clamp in the closed position, and producing a 10 N gripping force. To open the clamp, the eight SMA wires (Ø 0.32 mm) are heated. As they shorten, the disk moves down and the gripper opens. The disk’s translation for a full opening is 1 mm. Each wire thus must be able to shorten 1 mm. Considering the 4% recovery strain, the overall length of the wires should be at least 25 mm.
This configuration allows perfect transmission of motion and forces between the wires and the motion disk (Fig. 6.26, part 3). However, the module must be long enough to include all the wires, meaning that the length of the actuation subset (Fig. 6.26, parts 2 to 7) must be at least 25 mm, leading to an overall length for this module of 37 mm. The parallel SMA gripper has though the same length than the motorized module but has lower bandwidth and holding force. A spring (not shown in the figure) provides the clamp closure.

**Net SMA wires – module 11.E**

To reduce the size of the gripper module, the only solution seems to place the 250 mm wires in such configurations that the overall length of the module is minimized.

Module 11.E has the same actuation principle of module 11.D (Fig. 6.27 and 6.28, part 1, 2, 3 and 4), the disposition of the SMA wires is different; the wires of solution 11.E are disposed like a net a net (Fig 6.27, part 5). The wires are not parallel to the module’s frame, but their insertion holes are shifted by two positions. To even reduce the length of the module while maintaining the length of the wires, the fastening diameters on part
2 and 3 are different. Basic trigonometry shows that using this configuration, the module length can be decreased to 21.5 mm. This wire positioning has a good wire-length/module-length ratio but presents different drawbacks.

![Figure 6.27 – Net SMA gripper](image)

When contracted, wires do not pull axially, leading to power loss as only the axial component of the pulling force is used to translate the mechanism; the residual force generates stress on the module frame. The SMA wires should be coated with a not conductive layer to prevent the occurrence of short-circuits when two wires overlap.

**Helicoidal SMA wires – module 11.F**

The helicoidal SMA gripper is the last evolution of this family of grippers (Fig. 6.28). The mechanical actuation is the same as the parallel SMA gripper (Fig. 6.26). The SMA wires (Fig. 6.28, part 5) are placed in an helicoidal way along the external surface of the module frame (Fig. 6.28, part 2). Each wire runs at a fixed distance with respect to the next one; there is no contact between the wires. The final segment of each wire (Fig. 6.28, part 7 and 3), is parallel to the module axis. Friction can reduce the wires net force.
For clarity reasons, only three SMA wires are illustrated in figure 6.28. The complete clamp is powered by 8 SMA wires. A prototype has been built to validate this wires disposition (Section 7.1.3).

![Figure 6.28 – Spiral SMA gripper](image)

### 6.7 – Detail design of the SMA grippers

A detail design of all the modules presented in Section 6.5 and 6.6 has been produced. Finite elements calculation has been carried out to verify the working conditions of all the components. To illustrate the design strategy, the design of the modules 11.B and 11.D is hereafter reported.

#### 6.7.1 – Detail design of SMA wires 2 – module 11.B

The size and position of the pulleys has been optimised to maximise the length of the SMA wires (Fig. 6.29). Each SMA wire is 67 mm long and opens the jaw 30°.
The pulleys, during the wires shortening, rotate slightly; this movement is favoured allowing clearance between the axis and the pulley. The pulleys, made by insulating material, are shaped to avoid contact between the wires.

The SMA wires are disposed in parallel to generate higher force. To simplify the assembly, the gripper is powered by a single long wire; the mechanic connection is in parallel, while the electric connection is in series (Fig. 6.30).

Figure 6.30 shows the link between the SMA wire and the jaw; the wire (Fig. 6.31, part 2) is disposed around three pins (Fig. 6.31, part 1) fixed on the jaw. An isolating plate (Fig. 6.31, part 3), connected by two M1 screws (Fig. 6.31, part 4), keeps the wires in the right position.
A tensioning system allows to gain the wire clearance lost during the assembly phase (Fig. 6.32). Each SMA wire extremity (Fig. 6.32, part 1) is electrically connected with the gripper electric plug (Fig. 6.32, part 5). Two screws (Fig. 6.32, part 3 and 4) secure these components to a conductive element (Fig. 6.32, part 2).

This system fixes mechanically the SMA wires; SMA material, if welded, looses its “memory”. The length of the wire is 0.42 m, its resistance is 20 $\Omega$/m, the electric current is 1000 mA. The gripper needs a tension of about 8.4 V and dissipates a power of about 8.4 W. The jaw is designed to host internally the return spring (Fig. 6.33).
The $\varnothing$ 10 mm gripper has an overall length of 27 mm, jaw included. Wire heating lasts about 0.5 s; the cooling speed depends from the heat exchange wire/environment. Cooling is quicker when the difference between the wire temperature and the environment is higher; for this reason it is better to use a SMA having high transition temperature.

**Dimensioning of the gripper**

The dimensioning of the module 11.B is now reported. The return spring is dimensioned to provide the force necessary to pseudo-plastic strain the cold wires (in martensitic phase), the required closing force of the clamp is $R=40$ N. Figure 6.34 gives a schematic view of the gripper.
The force “F” generated by the wires, is function of the gripper geometry:

\[ F = \frac{1}{a} R \quad (1) \]

The length “L” of each wire depends on two parameters: the opening angle of the gripper “\( \varphi \)” and the mini-arm “a”:

\[ L = \frac{a \cdot \varphi}{4\%} \quad (2) \]

The shortening of “L” is 4%. The influence of the length “\( \alpha \)” is now analysed; it is better to have a long “\( \alpha \)” to exert higher forces “F” with the same number of wires (equation 1), but at the same time, a short “\( \alpha \)” reduces the length of the SMA wire (equation 2). A limited number of long wires simplifies the assembly (“\( \alpha \)” high). The parameters can vary as follows:

\[ 5 \text{ mm} \leq l \leq 10 \text{ mm}, \quad 1 \text{ mm} \leq \alpha \leq 5 \text{ mm} \]

\[ 30^\circ \leq \varphi \leq 60^\circ, \quad 1 \leq n \leq 10 \]

Figure 6.35, shows the specifications of the commercial NiTiNol wire from Mondotenics (MondoTronics04).

<table>
<thead>
<tr>
<th>Wire ( \varnothing ) (mm)</th>
<th>0,254</th>
<th>0,30</th>
<th>0,375</th>
</tr>
</thead>
<tbody>
<tr>
<td>F, force generated (N)</td>
<td>9,12</td>
<td>12,26</td>
<td>19,61</td>
</tr>
<tr>
<td>G, restore force (N)</td>
<td>1,6856</td>
<td>2,4010</td>
<td>3,8514</td>
</tr>
</tbody>
</table>

*Figure 6.35 – SMA wire specifications*

The following parameters have been fixed;

\[ R=40 \text{ N (specification), } L=67 \text{ mm (geometry)} \]

wire \( \varnothing=0,254 \text{ mm, } l=5 \text{ mm, } \alpha=5 \text{ mm, } \varphi=30^\circ \).

The resulting number of wires is 6.
The force “G” of the spring is necessary to restore “n” SMA wires:

\[ G = n \cdot G_i \]

Using the 0.254 mm diameter wire and \( n=6 \) we obtain:

\[ G = 6 \cdot 1.69 = 10.14 \text{N} \]

The bending moment of the spring is:

\[ M_j = G \cdot a = 50.7 \text{Nmm} \]

This is the value of the minimum torque necessary to deform the wires; when the jaw is open the torque increases generating a torque max \( M_{j_{\text{max}}} \). When the jaw is closed, the spring moment decreases. The spring is now dimensioned; as hypothesis the torsion spring is load only by a bending load. The wire diameter is:

\[ d = \sqrt[4]{\frac{64 M_{j_{\text{max}}}}{E \phi}} \cdot \frac{iD}{i} \]

where:

- \( i \)=number of coils;
- \( d \)=wire diameter of the spring;
- \( D \)=spring diameter;
- \( \phi \)=preload angle;
- \( E \)=Young's modulus.

Figure 6.36 shows a comparison of the two SMA actuations; SMA for opening (module 11.A) and SMA for closure (module 11.B), fixed the parameters: \( R=40 \text{N} \) (specification), wire \( \varnothing=0.254 \text{mm}, l=5 \text{mm}, a=5 \text{mm}, \phi = 30^\circ \).
In the second case the spring torque is lower (less restoring force required), the diameter “d” of the spring is smaller (compact solution) and the number of SMA wires is less (easier design).

6.7.2 – Detail design of helicoidal SMA wires – module 11.D

Eight SMA wires are placed in parallel and electrically connected in series for the proposed 11.D gripper actuation. A force must be applied to pull the wire back to its original length. This force is usually produced by a compression spring. The combination of SMA wires and a compression spring defines a linear actuator.

The actuation principle is shown on figure 6.37: when the wires are heated, the disk moves on the left and the gripper opens. When the wires are cooling, the disk moves to the right and closes the gripper. When the wires are totally cold, the gripper is closed. As the spring is pre-tensioned, it still exerts a force on the motion’s disk. This force is propagated through the jaws to the needles, allowing to firmly hold it.

As during most of the surgical procedure, the clamp is closed, the SMA wires are heated only during a very short time. To open and close the gripper, this available
translation must be converted into rotation (Fig. 6.37).

![Figure 6.37 – Gripper opening-closure](image)

This is achieved in the proposed design (Fig. 6.38), by pins (Fig. 6.38, part 1) that translate into oblong holes (Fig. 6.38, part 2).

The SMA based linear actuator produces a translation of the motion disk (Fig. 6.38, part 3) on a guiding shaft (Fig. 6.38, part 4) fixed to the module's frame (Fig. 6.38, part 5). A spring (Fig. 6.38, part 9) generates a force opposite to the SMA wires (Fig. 6.38, part 8). Two asymmetric pins (Fig. 6.38, part 1) are mounted on the motion disk.

![Figure 6.38 – Actuator assembly](image)
The gripper jaws (Fig. 6.38, part 6) rotate with respect to a shaft (Fig. 6.38, part 7) mounted on the motion’s disk’s guiding shaft. They are though rotating with respect to the module frame. The technical drawings of the clamp are reported in the Appendix A. This mechanism transforms the translation of the motion disk into a translation of the pins in the oblong holes. This motions results in the rotation of the gripper jaws with respect to their axial shaft and thus the opening-closing motion of the gripper.

In case of failure of the robotic mini-arm, the surgeon extracts the tool and ends the operation using classic instruments. If the four SMA wires are broken, the spring pushes the clamp in the closed position leaving the suturing needle secured to the clamp. This effect is positive, because the clamp, in the closed position, doesn’t offer resistance while it passes trough the trocar.

**Dimensioning of the gripper**

The design of this gripper must satisfy multiple criteria: it must minimize the overall length, produce a high clamping force, allow large opening of the gripper and should host 8 small SMA wires to allow fast response.

The following parameters, illustrated figure 6.39, must be set to design the gripper jaws:

\[ \Delta X \] – Translation range of the motion’s disk.

\[ \Delta h \] – Vertical distance between the pin’s position in opened and closed position.

\[ X_{axis} \] – Distance between the pins and the rotation axis in closed position.

\[ X_{needle} \] – Distance between the needle and the rotation axis, in closed position.
Opening range ($\theta_{ouv}$) and holding force ($F_{hold}$) are directly related to these parameters through the following equations:

$$\theta_{ouv} = 4 \arctan \left( \frac{\Delta h}{2(X_{axis} + \Delta X)} \right);$$

$$F_{hold} = \frac{F_{pre} \Delta h}{2X_{needle}};$$

So to get maximum opening range and holding force, Dh must be maximized and Xaxis, DX and Xneedle minimized.

However, to ensure good motion transmission, DH and DX must be related:

$$\Delta h = \alpha \Delta X$$

The angle made between the oblong hole and the gripper is calculated as:

$$\beta = \arctan \left( \frac{\Delta h}{\Delta X} \right)$$

If $\alpha$ is big, then $\beta$ is big and the oblong hole is almost vertical, meaning that very fast opening but low accuracy occur. If $\alpha$ is small, then $\beta$ is small, and the opposite will happen: very slow opening with good accuracy.

SMA wires of 250 microns diameters are used. 375 microns could only be used only for the parallel SMA gripper, as their bending radius is large.

The maximum stress of the wires is set by the provider to be 400 Mpa. The maximum
pulling force to be applied on the disk is calculated by the following equation:

\[ F_{\text{max}} = 8. \frac{\pi d^2 \sigma_{\text{max}}}{4} = 157 \text{N}; \]

and as \( F_{\text{max}} = F_{\text{prec}} + F_{\Delta x} = K(\Delta X_{\text{prec}} + \Delta X); \)

\( \Delta X_{\text{prec}} + \Delta X = \frac{F_{\text{max}}}{K}; \)

The chosen spring has the following characteristics: outside diameter: 5.2 mm, wire diameter: 1 mm, zero load length: 9.5 mm and stiffness \( K = 108 \text{ N/mm}. \)

The maximal compression of the spring is though:

\( \Delta X_{\text{prec}} + \Delta X = 1.454 \text{ mm}; \)

Opening angle and holding force can be re-written as:

\[ \theta_{\text{ouv}} = 4 \arctan \left( \frac{\alpha \Delta X}{2(X_{\text{axis}} + \Delta X)} \right); \]

\[ F_{\text{hold}} = \frac{\alpha K \Delta X(1.454 - \Delta X)}{2X_{\text{needle}}}; \]

So the design of the gripper resumes to the choice of \( \alpha, \Delta X, X_{\text{axis}} \) and \( X_{\text{needle}} \) to maximize \( \theta_{\text{ouv}} \) and \( F_{\text{hold}} \). It clearly appears that \( X_{\text{axis}} \) and \( X_{\text{needle}} \) must be minimized.

They are set respectively to 2 mm and 4 mm, to account for mechanical constraints and minimal distance needed to finely manipulate the needle. Figure 6.40 shows the evolution of the needle holding force with respect to \( \Delta X \) for 3 values of \( \alpha \):

\( \alpha = 1 \rightarrow \beta = 45^\circ; \quad \alpha = 2 \rightarrow \beta = 63^\circ; \quad \alpha = 3 \rightarrow \beta = 72^\circ \)

It clearly appears that \( F_{\text{hold}} \) reaches a maximum for \( \Delta X = 0.72 \text{ mm} \).
Figure 6.40 – Needle holding force vs displacement

Figure 6.41 shows the evolution of the needle holding force with respect to $\theta_{\text{mov}}$ for the same values of $\alpha$ and when $\Delta X$ increases. Each maximum of the curves is reached for $\Delta X = 0.72 \text{ mm}$. It also shows that the higher $\alpha$ is, the higher the holding force and the opening angle are. Again, high values of $\alpha$ must be balanced by low accuracy in the motion transmission.

Figure 6.41 – Needle holding force Opening angle

According to these considerations, the final design parameters for the gripper are set as (Fig. 6.42):
\[ \Delta X_{\text{preconstrained}} = 0.73 \text{ mm}; \]
\[ \Delta X_{\text{max}} = 0.72 \text{ mm}; \]
\[ \Delta h = 2 \Delta X_{\text{max}} = 1.42 \text{ mm}; \]
\[ X_{\text{axis}} = 2 \text{ mm}; \]
\[ X_{\text{needle}} = 4 \text{ mm}; \]
\[ K = 108 \text{ N/mm}; \]
\[ \text{Wire diameter} = 0.250 \text{ mm}; \]
\[ \theta_{\text{out}} = 60 \text{ degrees}; \]
\[ F_{\text{hold}} = 15 \text{ N}; \]

![Figure 6.42 – Needle holding force Opening angle](image)

To achieve the desired translation, the SMA wires must shrink by at least 0.72 mm. After a few cycles, the recovery strain of the wires is about 4%. As a security factor, the SMA wires length is calculated to produce a 1 mm translation. To achieve this 1 mm translation under the 4% strain constraint, each wire must be at least 25 mm long.

Using the helicoidal property of the wire configuration, its length \( L \) is given by:
\[
L = \sqrt{\pi^2 d^2 + h^2},
\]
where \( d \) and \( h \) stand respectively for the helix diameter and height.

As 8 wires are placed on the same frame, the helix angle must be calculated in order to avoid contact between the wires, so \( d \) and \( h \) must be related. After calculation and considering a wire of diameter 0.250 mm, the following relationship must be verified:
\[
h = 0.65d,
\]
giving an helix angle of 11 degrees.

The minimum frame diameter to get a 25 mm long wire is though given by:
\[
d = \frac{L}{\sqrt{\pi^2 + 0.65^2}} = 7.8 \text{ mm} \Rightarrow h = 5.1 \text{ mm}
\]

The overall length for the helicoidal SMA gripper would though be 17.1 mm.

The only drawback of this design would be friction and tightening between the frame cylinder and the wires, which could reduce the clamping force. Because these effects are
complex to model, it is necessary to carry out experiments. A prototype of the actuation main frame has been developed to validate the helicoidal wire disposition, in terms of force and position (Chapter 7).

6.8 – Modules interface

The mini-arm components and the mini-arm tools has been designed following a modular approach. Modular design simplifies greatly production and maintenance. All the modular parts are joined together using a standard common interface. Once the interface is defined, any company can design a modulus to be integrated into the system: basically software and hardware of this project are open source. It is possible to simplify the interface design encoding the signal information into the power signal.

The availability of these purposely designed mini-arms suggests a co-robotic approach to surgical operations. The idea of replicating human habits, with three incisions and the use of a camera and two hands can be reconsidered. We can now develop co-operating devices, with task-specific specialization, so that the individual task is directly and safely accomplished by specially developed effectors. Thereafter, no more than two incisions will be requested, lowering invasiveness. Without entering into details, the instrumental capabilities of co-robotic surgeons can be enhanced using tools and mission control strategies.

6.9 – Modules open chains

Section 6.5 and 6.6 have presented a selection of the designed modules; each module has its own characteristics like number of DoF, torque, size or weight.

It is not trivial to chose which module sequence can accomplish best a given surgery procedure. To solve this problem, a design methodology based on multi-objective
evolutionary algorithms has been developed: a population of randomly generated mini-arms is formed. Each mini-arm, created during this optimization process, must be evaluated with respect to its capability to perform the surgical gestures. The evaluation is performed through a realistic simulation of the surgical procedure.

The realism of this simulation, and thus the validity of the proposed mechanisms, is emphasized using experimental data of the CABG gesture, integrating 3D virtual models of the thoracic organs and adapting a kinematic control of the simulated mini-arms, able to deal with redundancy.

Each mini-arm is evaluated through 4 criteria:

- Capability to perform the gesture
- Manipulability of the mini-arm during the gesture
- Minimal distance between the mini-arm and the organs
- Maximum joint torque needed to perform the gesture.

The multi objective optimization results in an optimal pareto front that represents the best mini-arms for each possible combination of the 4 objectives. The choice of the mini-arm to be built is left to the designer, depending on the relative power he wants to give to each objective (Sallé04b).

Modules mechanical design and mini-arm optimization has been performed in parallel. Figure 6.43 and 6.44 show two mini-arms in the optimal pareto front; the mini-arms have respectively overall 7 and 6 DoF (including the gripper DoF). Both can perform the gesture while avoiding organs. Manipulability during the procedure is slightly higher for the first mini-arm. However, as this small difference implies a greater complexity in the construction, the second mini-arm has been chosen as optimal. The actuation
module 3.C is recurrently the last module of both the optimal mini-arms because it is compact and its gross-rotation can directly drive the rotational motion of the needle.

**Figure 6.43 – 6 DoF mini-arm**

**Figure 6.44 – 5 DoF mini-arm**

### 6.10 – The mini-arms dispenser

The advent of the articulated mini-arm changes the nature of the full size arm tasks. When the stick is replaced by the mini-arm, the full size arm loses full control over the end-effector; the position and control of the tip is obtained by a cooperation between the full size arm and the mini-arm. To simplify the overall design, it is possible to replace the full size arm with a lighter architecture.

Some basic considerations about serial robots are now reported. Consider a basic robot composed of only one, 1-DoF module (Fig. 6.45). The symbol “X” in the pictures represents the target position of a reference point of the end-effector. The robot in figure 6.45, left, has a small workspace. Of course, increasing the length of the module (Fig. 6.45, right), the robot can reach targets more far. It is not possible to state, in general, which of the two solutions is better; the length of the module has to be chosen once the position of the target is known. When the position of the target is unknown, a
"variable length" module is a suitable option.

![Figure 6.45 – Modules length](image)

Similar considerations apply for the optimal number of degrees of freedom of a serial mini-arm composed of several modules. If it is long, problems are encountered once trying to reach with the end effector targets close to the first modules of the robot without interfering with objects present in its surroundings (in our case some organs). A natural solution is to increase the number of modules as a function of the distance between the robot base and target point (Fig. 6.46). The “amount” of robot inserted in the patient abdomen changes depending on the position of the organ to be reached.

![Figure 6.46 – Optimal number of DoF](image)

A further remark is that the end-effector might not be able to reach a target because it is bad positioned respect to the obstacles present in the workspace. For example, the
robot in figure 6.47 can reach the target only if initially positioned on the left of the obstacle. A satisfactory robot architecture, for the prospected surgical application, should solve this “insertion problem”.

![Figure 6.47 – Insertion problem](image)

One of the features of the control algorithm for such robot is the capacity of handling and exploiting “multiple solutions” (Fig. 6.48).

![Figure 6.48 – Multiple solutions](image)

Following the outlined considerations, a natural setup for the surgical robot is a snail-like architecture (Fig. 6.49 and 6.50). The mini-arm, having “variable length” and a “variable number of DoFs”, solves the “insertion problem”. The problem of “multiple solutions” is addressed by the control algorithm (Chapter 7).
The surgical tool is a mini-arm, stored inside a dispenser, able to come out of the dispenser and to enter into the patient body. Different configurations can be studied; for example, the mini-arms could be wound like a cable reel and pulled out by two driving wheels located at the dispenser exit.
The mini-arm tail is fixed on the rotating central core of the dispenser. Power and control signals are sent from and to the mini-arm by the dispenser core. The dispenser has to be secured close to the patient body; it can be located, for example, on a small table or directly on the patient body.

A set of mini-arms, carrying cameras and heavy duty end effectors, cooperate during the surgical operation. A possible setup of three co-operating mini-arms is shown in figure 6.51. This setup can be placed above the patient abdomen by a suitable positioning system (Frumento06). Then the three mini-arms enter inside the patient and perform the surgical operation.

Figure 6.51 – Setup for three cooperating mini-arms
6.11 – Summary of design decisions

The designs introduced in the chapters 5 and 6 are now quickly summarized. For each design the main technical problems are recalled, the solutions more interesting are highlighted.

From a comparison between the proposed mini-arm shapes (Section 5.4) the mini-arm with universal-joints (Section 5.4.3), actuated by electric motors, has been selected (Fig. 6.52).

Electric motors actuation is preferred to cable actuation because, despite it provides low torque, it offers high modularity. Universal joint articulation gives high dexterity to the mini-arm.

Subsequently a wide range of modules powered by electric motors has been designed;
The mini-arm modules are subdivided into two main families; actuation and end effectors modules. There are three types of actuation modules; 1 DoF bending modules (Section 6.4.1), 1 DoF axial modules (Section 6.4.2) and 2 DoF modules (Section 6.4.3). Module 1.C is the favourite bending module (Fig. 6.53); motor and angular sensor are well integrated into the module frame, worm and gear coupling give torque compatible with the surgical needs.

![Figure 6.53 – Bending modules](image)

The assembly of 1 DoF axial modules (Fig. 6.54) is generally difficult. Module 2.C is the
favourite axial module for two reasons; it provides high torque and it uses a cheap sensor (2SA-10 Sentron Sensor costs about 18 Euro while F.W. Bell sensor BH-205 costs 366 Euro, year 2003). The main drawback is its the length.

Each 2 DoF module (Fig. 6.55) has the advantage to be more compact than the equivalent sequence of two 1 DoF axial modules (Fig 6.53 and 6.54). The mini-arm with universal-joints (Fig. 6.52) can be created assembling a sequence of 3.C modules; this module has the advantage to be compact and the drawback to be complex.
TECHNICAL PROBLEM
- The face gears are not available
- Conic gears not usable
- Where to put sensors?

Figure 6.55 – 2 DoF modules

TECHNICAL PROBLEM
- Assembly is complex
- Frame is fragile
- Motors fix is weak

Figure 6.56 – End effectors

TECHNICAL PROBLEM
- Integrate into the system position and force sensors
- Control the blade advance
- See exactly were the end-effector is cutting

TECHNICAL PROBLEM
- Fix the end effector respect to the organ
- Assembly is complex
- Rotation of the syringe needle

TECHNICAL PROBLEM
- High clamping force is required
- Friction between clamps and needle is generally low
- For manipulability reasons final module needs to be short

TECHNICAL PROBLEM
- Throw out the sewing wire from the spiral
- To tension the sewing wire
- To knot the sewing wire

TECHNICAL PROBLEM
- SMA spring is an actuator slow and difficult to control
- Integration of the pipe delivering the actuation fluid along the mini-arm

TECHNICAL PROBLEM
- The module offers limited torque due to the intrinsic low power of the electric motors

TECHNICAL PROBLEM
- It is difficult to assembly the SMA wires; wires cannot touch each other to avoid short circuit
Figure 6.57 – Grippers

Figure 6.56 depicts some examples of the mini-arm end effectors; scalpel (Section 6.4.4), syringe (Section 6.4.5), gripper (Section 6.4.7) and sewing machine (Section 6.4.6). The sewing machine could highly simplify the minimally invasive sewing procedures. Figure 6.57 shows the gripper family. Finally figure 6.58 reports two possible configurations of the mini-arm; on both the examples a clamping tool is mounted as end effector (Section 6.7).
Design of modular end-effectors

TECHNICAL PROBLEM
- High clamping force is required
- Friction between clamps and needle is generally low
- For manipulability reasons final module needs to be short

Figure 6.58 – Mini-arm architecture configurations A and B

The designed mini-arm can be generally used as an end effector of a surgical arm; three solutions are shown and compared (Section 6.7). The mini-arm can be mounted on a “classic industrial arm” like da Vinci® (Fig. 3.27 a), can be integrated into a light arm like Grenoble arm (Fig. 3.16) or LRP arm (Fig. 3.40), or can be embedded into a mini-arm dispenser (Fig. 6.50). The mini-arm dispenser is the preferred solution because it enhances the modularity of the whole surgical device while keeping limited the production costs (Fig. 6.59).

Figure 6.59 – Full robotic arm
Chapter 7

Implementation & system integration

The mini-arm described in Section 6.4 is composed by an open (serial) chain of modules. The design of each module is based on calculations made with supplier’s data and theoretical values for some parameters. However, due to the size of the different parts and the low precision of some supplier’s datasheet, friction or inertia are almost impossible to model; experimental validation of the selected designs is thus necessary. Section 7.1 shows the prototypes of a selection of modules and describes their mechanical performances. Section 7.2 addresses the problem of the control of the whole surgical instrument.

7.1 – Modules prototypes and control

The prototypes of the bending module 1.C, of the two grippers 11.B and 11.F are hereafter described. Finally the prototype of the full mini-arm is presented. The frames of the modules are composed by plastic and aluminium to keep the weight light.
7.1.1 – Bending module – module 1.C

A 1:1 scaled prototype of the module 1.C has been machined and assembled as illustrated on figure 7.1. The micromotor, worm and gear transmission, magnet, magnetic sensor and electronic board are clearly visible.

![Prototype of the module 1.C](image)

*Figure 7.1 – Prototype of the module 1.C*

The control of the module is achieved through a real time controller developed on Linux RTAI, using a PID control scheme. Figure 7.2 shows the results obtained for the controlled module: the mechanical joint range is ± 104°, but the module is controlled between ± 90°. The control results show that the module takes 2.5 seconds to rotate 180°, leading to a maximum speed of 72 °/s; this speed is compatible with the speeds needed during a surgical procedure.
The module’s available torque has also been tested: a 79 grams mass has been fixed to the module’s mobile part (Fig. 7.3).

The module has been placed so that the torque generated by gravity on the joint increases when the module lifts the weight, as illustrated on figure 7.3. The module is placed at -90° (vertical position) and controlled to lift the weight up to 0° (horizontal position). When the module stalls, the equilibrium between gravity torque and available joint torque is reached. A simple cosine function allows to calculate the available torque.
Experimental results are shown on figure 7.4. The module can reach -10° constantly and sparsely get closer to -7°. The equilibrium is thus reached for theta equal to -10°. The distance between the modules axis and force application point being 7.5 mm, the available torque is 5.8x10⁻³ Nm. This is close enough to the awaited 6.0x10⁻³ Nm to validate the design principle and mechanical capacities for this module and thus for all the proposed modules.

![Torque Measurement](image)

*Figure 7.4 – Response of the module under external load*

### 7.1.2 – SMA wires 2 – module 11.B

A physical mock-up of the gripper 11.B has been produced (Fig. 7.5); the frame is formed by an U aluminium profile, two brass connections keep the wire under mechanic tension. The device is powered by only two 0.12 mm Ø SMA wires to simplify the assembly procedures; the transition temperature of the wire is 130 °C. A steel spring is located inside the wood jaw (Fig. 7.6). Teflon pulleys offer electric insulation, low friction and an high melting fusion.
The prototype created gives information about the SMA cooling time: this datum is complex to compute theoretically. The module, powered by 4 V @ 400 mA (Fig. 7.7), can create a force of 2 N; in a 24 °C environment (natural convection), the bandwidth is about 1 Hz. SMA migrates gradually from the martensitic to austenitic phase, this transformation suffers hysteresis; the literature proposes different non-linear algorithms for the control of SMA actuators (Grant97, Majima01, Kumagai00).

The prototype tested (Fig. 7.5), is a simplified version of the preferred solution (Fig. 6.24): future developments will include the realization of a prototype identical to the preferred solution. The gripper bandwidth can be increased blowing on the SMA wires.
the CO₂ used to inflate the abdomen patient. An accurate control of the gripper has still to be implemented. The tool still lacks force feedback; as future development, pressure sensors could be placed on the gripper jaws (Flemming97, Ortmaier03).

7.1.3 – Helicoidal SMA wires – module 11.F

A prototype of the actuation system of the module 11.F has been built (Fig. 7.8); each wire runs at a fixed distance with respect to the next one (Fig. 7.8, part 1). The final segment of each wire is parallel to the module axis (Fig. 7.8, part 2). Friction and tightening around the module’s frame could reduce the actuation force. The first results obtained testing the prototype show good capability. For machining convenience, the
frame of the module is set to: length: 5.6 mm; wire tightening diameter: 8.7 mm (Fig. 7.8). The spring is 0.7 mm pre-loaded.

The SMA wires have been electrically connected in series and heated using a 0.8 A or 0.9 A current for 20 seconds. The resulting displacement is shown on figure 7.9 and 7.10 for two trials. For the first trial (Fig. 7.9), at the beginning, the position changes quickly as the motion disk moves down. However after only 8 seconds, the displacement stabilizes to 0.55 mm even while the current is maintained.

When the current is stopped, the motion disk remains at this position during 22 seconds before starting moving.

![Figure 7.9 – Helicoidal SMA gripper results](image)

This behaviour corresponds to friction: in the heating phase, the force necessary to move the disk increases as position is increasing. When the available force gets lower to friction, the disk stops.

During the cooling phase, the same behaviour happens: the wire needs some time to cool down and start its phase change. During this time, it is still stiff, keeping high friction. When cooling down, the wires get more elastic and friction is reduced, the disk
moves back to its initial position.

For this second trial (Fig. 7.10), the behaviour is slightly different: at time = 21 s, the position increase corresponds to the wires overwhelming friction and allows translation. The same behaviour is repeated at time = 60 s during cooling phase. However, this friction limits the ability of the system to get back to its initial position as it stabilizes at 0.1 mm.

![SMA Helicoidal Gripper](image)

*Figure 7.10 – Helicoidal SMA gripper results II*

These experiments have shown that the desired displacement is not reached, due to friction problems: most of the power generated by the SMA phase transformation tightens the wire around the frame; only a small amount of this power pulls the motion disk. This is mainly caused by friction between the wire and the frame, and inside the wire, when bent to align with the motion disk. This friction is even increased when the wire is heated as the tightening force around the frame increases. The overall power efficiency of the system shows to be rather low. To reduce this power loss, the helix angle of the wires should be increased, either by increasing the length of the frame or by stopping the helix at half a turn, or even less.
More experiments are thus necessary to determine the best combination of height, diameter and helix angle for this helicoidal actuation. However, this embodiment allows a great reduction of the size of the gripper. The proposed 11.F MIS gripper though uses the helicoidal SMA gripper as it is compact, lightweight and satisfies the gripper design criteria. This gripper lacks force feedback.

Despite the modules 11.B and 11.F have been designed to satisfy surgery needs, these grippers can be employed even in other fields such as microassembly, mini-samples grasping, space robotics and biological labs.

### 7.1.4 – Full mini-arm

The preferred mini-arm is formed by four modules (Fig. 7.11); a bending module 1.C (Section 6.4.1), two DoF modules 3.C (Section 6.4.3), and a gripper module 11.D (Section 6.4.11).

![Figure 7.11 – Mini-arm modules sequence](image)

Figure 7.12 reposts another view of the preferred the mini-arm (Fig. 6.58, configuration B).
Figure 7.12 – Digital mock-up of the final configuration of the instrument

Figure 7.13 collects the photos of some of the modules that have been machined. The prototype of the mini-arm (Fig. 7.12), has been created and tested (Fig. 7.14). The performance of the instrument is satisfactory; each electric motor can exert on its joint a torque of at least $4 \times 10^{-3}$ Nm.

Figure 7.14 – Full mini-arm configuration B

A main computer controls the mini-arm. At the moment there are many electric wires that run along the mini-arm; some wires supply power to the motors, other wires
communicate, to/from the computer, the kinematics and control data.

Before to test the instrument in vivo, cabling has to be improved. The size of the cables
can be reduced, moreover the number of cables can be decreased by Bluetooth communication or embedding power and control signals in a single wire (Section 7.2).

The modules have been designed and prototyped in collaboration with the PhD Damien Sallé, from the University of Paris 6, and the engineer Filippo Morra (module 11.B), from the University of Genoa.

### 7.2 – Control of the mini-arm

Today computational power limits the control capabilities. Ideally the 3D models of the patient organs, created from preoperative images, should be overlapped to real organs and continuously updated; the model of each organ should have the same shape, volume, elasticity and resistance to cut of the real one. Real time control implies virtual and real organs to be exactly matched at least 30 times for second. The surgeon should be able to try each step of the surgery procedure on the virtual organ. The surgeon will ask the robotic platform to reproduce the operation with the mini-arms on the real organ only when fully satisfied by the digital forecast of the virtual operation. Like a chess game, surgery robotic platforms will continuously predict, considering the actual situation, vital parameters and status of advance of the operation (Ortmaier03), the side effects and the risks related to errors of each possible surgery action. A good prediction algorithm can foresee far in the future (next 5, 10, 100 actions) and the better solution should be interactively suggested to surgeon. This intensive computation helps to enhance the operation rate of success.

Today (December 2004) the biological modelling of deformable objects is still object of research, moreover the digital processing that allows to transform complex 3D images (organs), into 3D curves cannot be executed real time due to lack of ‘optimised
software’/’computation power’. For this reason, the 3D model of the patient body cannot be upgraded in real-time. Often, depending on the hospital equipment or on the surgical operation, a detailed preoperative model of the patient organs is not available. These considerations have suggested to design a mini-arm control that doesn’t need preoperative data, to work.

The control set ups is described in the following sections. Simulation and control can be performed imposing positions, either forces, or both positions and forces.

Different control strategies for redundant mini-arms can be implemented (Wunderlich04, Bowling98). Generally redundant arms, with number of internal DoF bigger than the number of task DoF (in our case the number of task DoF is 6), are designed to accomplish complex tasks that could be not performed easily by arms having full mobility (n° DoF = 6). Redundancy itself is not sufficient to guarantee the success of a general mission. Examples of goals are: to avoid obstacles, to pass through narrow openings, to minimize power consumption, to minimize the required motor torque, to maximize the mini-arm speed etc. Some missions require, at the same time, to simplify more than one goal (single or multi-object optimization). The relative relevance of each not mandatory goal is normally declared assigning to it a weight.

To simplify the problem, the control can be distributed; each module receives local low priority constraints from the neighbour modules and high priority constraints from the global control (Kuhl03). Local control copes with low level constraints like contacts, while global control ensures that the overall mission is accomplished. Figure 7.15 shows the mini-arm robot control levels. The control core strategy proposed has a layered structure and is based on purposely written kinematics and dynamics models.
Sometimes, the working environment is unknown; in the case the instrument is inserted into a cavity, like the intestine, the module close to the head of the instrument gives precious information about the intestine shape to the following modules.

The same modular approach used for the mechanical architecture can be adopted for the control strategy. Co-operative surgery needs to progress following suitably controlled actions:

- to gently insert the co-robot inside the body, without damaging any organ;
- to position the surgical instrument, taking into account the remote inspection camera.
- to establish a solid link between the surgical instrument and the selected organ;
- to accomplish the planned actions, verifying the task progression;
- to detach and retrieve the instrument, with preservation of results and surroundings;
- to switch to the subsequent task, according to the operation schedule.

The functional characteristics of the robot change depending on its structure. The
workspace, for example, is function of the mobility of the modules and of the instrument architecture in the modules sequence. The singular configurations of the robot change as well. This information has a fundamental importance in the control of the robot. An easy way to adapt the control to any new setup of the system is to refer to a database of workspace and functional data, such as reachable regions and singular surfaces for the different robot setups (Appendix E). The database can be also used to determine the best mini-arm architecture for any specific operation.

The surgery mini-arm, potentially, can be used for a wide range of minimally invasive operations. A detail human 3D model has been assembled, to virtually verify which types of procedures are compatible with the instrument size and dexterity. The human body is provided with organs and skeleton (Fig. 7.16).

![Model of human body](image)

**Figure 7.16 – Model of human body**

### 7.2.1 – Control future implementations

Multiprocessor control is a classic solution for complex real-time miniaturised robots (Fatikow97). The humanoid robot morph3 (Furuta02) has a control scheme quite similar to the one retained for the mini-arms. The main CPU (MIPS VR5500) controls different sub CPU modules; all the sub CPUs are connected to the main CPU thanks to a LAN network. The mini-arms local CPUs (and the morph3 sub CPUs) can only make
low level decisions. The morph3 CPU net is able to control in real time 30 DoF and 102 sensors. The 360 mm high morph3 robot can walk and make acrobatic motion.

The mini-arm will be controlled by a distributed logic algorithm, supervised and synchronized by a central unit. Each instrument segment is provided with sensors, a small CPU, an EEPROM and a radio communication interface (Bluetooth): the EEPROM contains the programs executed by the local CPU and is used to save data. Each CPU interprets the signals of the peripheral sensors and commands its local actuators. The central unit is a computer, located in the surgical theatre and equipped with a radio communication interface (Bluetooth). The radio network allows rapid wireless data-transfer between each local CPU and the central unit. Communication among the small CPUs is also possible. The central unit allows each local CPU to take autonomously only low level decisions. An example of a low level decision is to permit active local joint compliance, if a sensor detects the collision of a module against an organ. Further changes apply to the device for specialized jobs.

The final release of the mini-arm, like a numeric control machine, will be able to change autonomously the surgical tool necessary for the operation.

The number of modules of the jointed mini-arm can vary depending on the kind of surgical operation that is to be performed; for example scaled size instruments could be used to operate on children. It may be necessary to modify the mini-arm configuration even during the operation. On such facts, a self-reconfigurable controller is a basic requirement, with local modules equipped with additional low level logic. The strategy is updated, once the module sequence and the effector type are acknowledged; the central unit assigns the actual task to the local CPU, so that the individual modules achieve their function. This logics modularity, together with the physical modularity greatly simplifies
maintenance; rather than on-process repair, the co-robot operation efficiency is deferred to replacing failed modules. Once the mini-arm is reassembled, the central and peripheral CPUs generate the new control code, depending on the new configuration.

A similar approach is adopted for the control of the German Aerospace Center (DLR) 3rd generation space arm (Fig. 7.17); the arm is formed by a sequence of identical modular elements. A dedicated software is able to generate automatically the control code, function depending on the arm configuration (Krenn04).

![Figure 7.17 – DLR 3rd generation mini-arm](image)

### 7.2.2 – Forward kinematics

The kinematics of this mini-arm is now analyzed. The robot is described using the Denavit Hartenberg convention (Fig. 7.18, 7.19, Craig86). The instrument has rotational joints and no translational joints.
The position and orientation of the end effector is computed by transformation matrices. The determinant of the Velocity transform matrix is used to verify if the considered mini-arm configuration is singular (Fig 7.20).

The mini-arm dispencer (Section 6.8) seems to be the best mini-arm carrier (Fig. 6.50). The mini-arm, wound inside the dispenser, potentially can have n DoF; the amount of mini-arm, which exits from the dispenser, depends on the surgery procedure. Figure 7.21 and 7.22 show respectively the geometry and the link parameters of the redundant robotic tool (dispenser + mini-arm).
The robotic tool, formed by the mini-arm of figure 7.12, located in the dispenser, is now considered. The geometry and link parameters of this full mobility tool are represented in figure 7.23. The instrument has overall 7 DoF; 1 DoF is given from the dispenser, 5 DoF are given by the mini-arm body modules, while 1 DoF actuates the gripper. It must be noted that, given the mini-arm modularity, unlike the industrial serial kinematics chain robots, where the positioning of the end effector is mainly due to the
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first three links and the orientation is due to the wrist (three last links), all the links of the surgery robotic tool contribute to the end effector pose (position and orientation).

\[
\begin{array}{cccc}
 i & a_{i-1} & \alpha_{i-1} & d_i & \theta_i \\
1 & 0 & 0 & 0 & \theta_1 \\
2 & L_1 & 0 & 0 & \theta_2 \\
3 & L_2 & -90^\circ & 0 & \theta_3 \\
4 & 0 & +90^\circ & L_3 & \theta_4 \\
5 & 0 & -90^\circ & 0 & \theta_5 \\
6 & 0 & 90^\circ & L_4 & \theta_6 \\
\end{array}
\]

Geometry

Link parameters

Figure 7.23 – Full mobility robotic tool: geometry and link parameters

The dimensions of the tool are: \(L_1=50\) mm, \(L_2=15\) mm, \(L_3=36\) mm and \(L_4=39.5\) mm.

The frames of the full mobility mini-arm has been assigned following the Denavit

Figure 7.24 – Full mobility robotic tool: frame assignment

7-20
Hartenberg convention (Fig. 7.24). The link transformations of the robot are illustrated in figure 7.25.

\[
0^T = \begin{bmatrix}
c_\theta_1 & -s_\theta_1 & 0 & 0 \\
s_\theta_1 & c_\theta_1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad 1^T = \begin{bmatrix}
c_\theta_2 & -s_\theta_2 & 0 & L_1 \\
s_\theta_2 & c_\theta_2 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad 2^T = \begin{bmatrix}
c_\theta_3 & -s_\theta_3 & 0 & L_2 \\
s_\theta_3 & c_\theta_3 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix},
\]
\[
3^T = \begin{bmatrix}
c_\theta_4 & -s_\theta_4 & 0 & 0 \\
s_\theta_4 & c_\theta_4 & 0 & 0 \\
0 & 0 & -1 & -L_3 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad 4^T = \begin{bmatrix}
c_\theta_5 & -s_\theta_5 & 0 & 0 \\
s_\theta_5 & c_\theta_5 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad 5^T = \begin{bmatrix}
c_\theta_6 & -s_\theta_6 & 0 & 0 \\
s_\theta_6 & c_\theta_6 & 0 & 0 \\
0 & 0 & -1 & -L_4 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Figure 7.25 – Full mobility robotic tool: link transformations

The single transformation, which relates the frame of the end effector with the base frame, is found multiplying the link transformation matrices (Appendix C). The position of the end effector of the full mobility robotic tool (Fig. 7.23) is given by:

\[
x = L_4 \left( (c_1 c_2 s_3 s_4) + (c_1 c_2 - s_1 s_2) s_3 c_4 \right) c_5 + L_3 (c_1 c_2 s_3 s_4) s_5 + L_2 (c_1 c_2 - s_1 s_2) s_3 + L_2 c_1 c_2 + L_2 s_1 s_2 + L_1 c_1 \\
y = L_4 \left( (s_1 c_2 + c_1 s_2) + (c_1 c_2 - s_1 s_2) c_3 c_4 \right) c_5 + L_3 (s_1 c_2 + c_1 s_2) c_3 s_5 + L_2 (s_1 c_2 + c_1 s_2) c_3 + L_2 c_1 c_2 + L_2 s_1 s_2 + L_1 s_1 \\
z = -L_4 s_1 c_5 c_5 + L_4 c_5 c_5 + L_3 c_3
\]

Where \( c_1 = c_{\theta_1} = \cos \theta_1 \) and \( s_1 = s_{\theta_1} = \sin \theta_1 \).

The coordinates of the end effector reference point (x, y, z), are expressed as function of the 6 internal coordinates (angular displacements of the rotational joints) of the robot. The matrix, describing the orientation of the end effector, is deferred to Appendix C.

**Robot workspace**

A special purpose Maple parametric algorithm has been written and set-up to compute
the robotic tool workspace; the algorithm, being general, can be used for any serial chain (Appendix C). The use of this module is shown in the diagram of the figure 7.26.

**Figure 7.26 – Workspace calculation**

The robot workspace is then analyzed in the case of real ranges at every joint; the point cloud obtained is represented using 3D visualisation commercial software (Fig. 7.27). Because of the workspace is symmetric respect to the z axis, only the points having positive z are displayed. The robotic tool workspace is like a torus or a disk; the diameter of the torus increases with the diameter of the dispenser, parameter L1 of figure 7.23. A yellow deformable cover lays on the points to better show the workspace boundary (Fig. 7.28).

**Figure 7.27 – Full mobility robotic tool: workspace I**

\[
\begin{align*}
L_1 &= 50 \text{ mm} \\
L_2 &= 15 \text{ mm} \\
L_3 &= 36 \text{ mm} \\
L_4 &= 39.5 \text{ mm} \\
-180^\circ \leq \theta_1 < 180^\circ \\
-90^\circ \leq \theta_2 < 90^\circ \\
0^\circ \leq \theta_3 < 180^\circ \\
-180^\circ \leq \theta_4 < 180^\circ \\
-90^\circ \leq \theta_5 < 90^\circ \\
-180^\circ \leq \theta_6 < 180^\circ
\end{align*}
\]
Figure 7.28 – Full mobility robotic tool: workspace II

The tip of the mini-arm exits from the dispenser through a door and enters into the patient body through the trocar. The door constraint is difficult to model; this constraint has to be applied each time to a different mini-arm module. The model used for the workspace computation (Fig. 7.23) doesn’t consider these two constraints (door and trocar). A simplified way of simulating the presence of the door is to fix the angular constraints:

-180° ≤ θ1 ≤ 180°
-90° ≤ θ2 ≤ 90°
0° ≤ θ3 < 180°
-180° ≤ θ4 < 180°
-90° ≤ θ5 < 90°
-180° ≤ θ6 < 180°

Figure 7.29 – Full mobility robotic tool: workspace III

FULL WORKSPACE

L1 = 50 mm
L2 = 15 mm
L3 = 36 mm
L4 = 39.5 mm
θ1 = 0°
-90° ≤ θ2 ≤ 90°
0° ≤ θ3 < 180°
-180° ≤ θ4 < 180°
-90° ≤ θ5 < 90°
-180° ≤ θ6 < 180°
position of the dispencer wheel ($\theta_1 = \text{const}$); in this case the mini-arm is all outside of the dispencer. The workspace becomes half a sphere (Fig. 7.29). The sphere is centred on the dispencer door. This half sphere is hollow (Fig. 7.30); as mentioned in section 6.10, when the mini-arm is all out, the end effector has problems to reach the points close to the centre of the half sphere. The size of the hole inside the sphere depends from the module lengths and DoF spam. These internal points can be easily reached decreasing the number of modules outside of the dispencer.

![FULL WORKSPACE](image)

**Figure 7.30 – Full mobility mini-arm: workspace II**

**Singularity analysis: screw theory**

The singular configurations of the mini-arm are singled out using screws (Gallardo03, Fig 7.31). Each body of the mini-arm serial chain is linked to the following one by a revolute joint. These joints are represented by screws ($0S^1$ to $5S^6$). A screw is, in general, an helicoidal joint; the revolute joints is a screw having pitch null. The mechanism is in a singular configurations if and only if the six joint screws are linearly dependent.
The mini-arm is a wrist-partitioned arm or decoupled manipulator; last three axes intersect at a common point C (Hayes02). Positioning and orienting problems can be considered separately. The presence of the spherical center of rotation C (last three links), allows to simplify the problem: the configuration is singular if one of the following conditions is satisfied:

A) the first three links $0s^1$, $1s^2$ and $2s^3$ (three revolute joints 3R) are linearly dependent;

B) the last three links $3s^4$, $4s^5$ and $5s^6$ (equivalent spherical joint S) are linearly dependent;

C) the first three links and the last three links (3R and S) are mutually dependent.

These conditions are satisfied under the following conditions;

A) $2s^3$ is parallel to the plane defined by $0s^1$ and $1s^2$; $\Rightarrow$ NEVER

B) $3s^4$ and $5s^6$ are parallel $\Rightarrow \theta_j = 0$;

C) $0s^1$ or $1s^2$ or $2s^3$ are through C $\iff \theta_j = -\arcsin\left(\frac{5}{12}\right)$ or $\theta_j = -\pi + \arcsin\left(\frac{5}{12}\right)$

$0s^1$, $1s^2$ and C are coplanar $\iff \theta_j = 0$;

$1s^2$ is parallel to the plane passing through $2s^3$ and C $\iff \theta_j = 0$ or $\theta_j = \pi$

---

*Figure 7.31 – Full mobility robotic tool: geometry and link parameters*
**Singularity analysis: Velocity transform matrix**

The singularities of the robotic tool can also be found using the Velocity transform matrix. A screw can be expressed in terms of Plücker coordinates:

\[ i S^{i+1} = (i \hat{s}^{i+1}, i s_0) \]

where \( i \hat{s}^{i+1} \) is a unit vector of the incremental rotation axis, and \( i s_0 \) is computed as:

\[ i s_0 = h_{i+1} (i \hat{s}^{i+1} + i \hat{s}^{i+1} \times \vec{r}_{0/P}) \]

The screw pitch is \( h_{i+1} \); in our case the pitch is null (Hayes02). The vector \( \vec{r}_{0/P} \) is directed from an arbitrary point P of the instantaneous screw axis to the point O. The Velocity transform matrix of the manipulator is computed assembling the local contributions of the six members:

\[ T_i = [0 S^1 \ldots S^m] = \begin{bmatrix} e_1 & e_2 & \ldots & e_m \\ e_1 \times \vec{r} & e_2 \times \vec{r} & \ldots & e_m \times \vec{r} \end{bmatrix} \]

The Velocity transform matrix (of the full mobility robotic tool) can be calculated respect to different frames; the matrix calculated by respect to the base frame is (Fig. 7.32):

\[
J_{\text{base frame}} = \begin{bmatrix}
0 & 0 & e_1 & e_4 & e_5 & e_6 \\
0 & 0 & e_2 & e_4 & e_5 & e_6 \\
1 & 1 & 0 & e_4 & e_5 & e_6 \\
0 & * & 0 & * & * & * \\
0 & * & 0 & * & * & * \\
0 & 0 & * & * & * & *
\end{bmatrix}
\]

*Figure 7.32 – Velocity transform matrix respect to the base frame*

The terms of the velocity transform matrix described with the symbol * can assume different values. The following conditions are always verified (Fig. 7.23 and 7.24):
z_1 axis is always parallel to z_0,  
z_2 axis is always parallel to z_0,

z_3 axis is always perpendicular to z_0,  
\( e_1 \times r_1 = 0 \) because \( r_1 = 0 \)

r_2 lays on plane x_0y_0  
e_2 is parallel to z_0  
\( e_2 \) is parallel to plane x_0y_0

r_3 lays on plane x_0y_0  
e_3 is parallel to plane z_0 \Rightarrow e_3 \times r_3 \) is parallel to plane z_0

The Velocity transform matrix is easier if computed by respect to the frame 4 (Fig. 7.33).

\[
J_{frame4} = \begin{bmatrix}
    e_1 & e_2 & e_3 & 0 & e_5 & e_6 \\
    e_1 & e_2 & e_3 & 0 & e_5 & e_6 \\
    e_1 & e_2 & e_3 & 1 & e_5 & e_6 \\
    * & * & * & 0 & 0 & 0 \\
    * & * & * & 0 & 0 & 0 \\
    * & * & * & 0 & 0 & 0
\end{bmatrix}
\]

**Figure 7.33 – Velocity transform matrix respect to the frame 4**

The determinant of the velocity transform matrix results (Fig. 7.34):

\[
\text{det}(T_v) = -5400 \cdot \sin \theta_2 \cdot \sin \theta_3 \cdot \sin \theta_6 \cdot (5 + 12 \cdot \sin \theta_3)
\]

As mentioned before the determinant is not function of \( \theta_1, \theta_4 \) and \( \theta_6 \).

The singular configurations can be found verifying when the determinant is null:

\[
\sin \theta_2 \cdot \sin \theta_3 \cdot \sin \theta_6 \cdot (5 + 12 \cdot \sin \theta_3) = 0
\]

This equation is satisfied if one of the following conditions is verified:

1) \( \theta_2 = 0 \);  2) \( \theta_3 = 0 \);  3) \( \theta_6 = \pi \);  4) \( \theta_6 = -\arcsin(\frac{5}{12}) \);  5) \( \theta_6 = -\pi + \arcsin(\frac{5}{12}) \);

6) \( \theta_5 = 0 \);

To each of these conditions, corresponds a set of points in the workspace (Fig. 7.34):
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<table>
<thead>
<tr>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
<th>$\theta_3$</th>
<th>$\theta_4$</th>
<th>$\theta_5$</th>
<th>$\theta_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>var</td>
<td>var</td>
<td>0°</td>
<td>var</td>
<td>0°</td>
</tr>
<tr>
<td>0°</td>
<td>0°</td>
<td>any</td>
<td>0°</td>
<td>var</td>
<td>any</td>
</tr>
<tr>
<td>0°</td>
<td>var</td>
<td>arcsin(5/12)</td>
<td>0°</td>
<td>var</td>
<td>any</td>
</tr>
</tbody>
</table>

*Figure 7.34 – Full mobility robotic tool: singularities areas I*
The singularity areas of figure 7.34 are now plotted in the same graph (Fig. 7.35). Please notice that the 3D surfaces graphed look elongates because the axes are not equispaced (ellipsoids instead of spheres).

The variable $\theta_1$ has the task to change the orientation of the mini-arm by respect to the surrounding environment; such input rotates the mini-arm rigidly as a whole without affecting the “internal” configuration of the mini-arm. $\theta_1$ is not able to change the relative position of the internal segments of the mini-arm. For this reason, once a singular configuration is found, it is possible to generate a set of configurations still singular, varying the value of the $\theta_1$ coordinate (and keeping unchanged the values of the remaining variables $\theta_2$ to $\theta_6$). Graphically, to each point of singularity, corresponds

Figure 7.35 – Full mobility robotic tool: singularities areas II
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a circle of singularities; the circle is positioned on a plane parallel to the plane $x_0y_0$ and has its center on the $z_0$ axis. Similar considerations apply for the variable $\theta_6$ (and $\theta_7$).

The singularity analysis mathematical model, based on the screw theory, has been reckoned by a Maple parametric module that can be used for any serial robot; the block diagram of the software module is shown in figure 7.36:

![Block Diagram of Software Module](image)

**Figure 7.36 – Singularities calculation**

Assigning to $\alpha_3$ a value slightly different from $-90^\circ$ (for example $-85^\circ$), the number of mini-arm singularities can be reduced.

The velocity analysis could be done by differentiating the position equations model; this method is cumbersome and requires a lot of computation, so the resulting values may be inaccurate.

**Database graphical output**

A discrete selection of the workspace has been computed. The data stored in the database are: joint angles, position of the end-effector, end-effector orientation, Velocity transform matrix. This database can be used to find different set of workspace points that satisfy any specific criteria. The instrument workspace (Fig. 7.29 and 7.30), can be limited imposing, for example, the surgery gripper to maintain a certain orientation during the surgery procedure. The workspace of figure 7.37 has been generated.
imposing the end effector frame to be parallel respect to the base frame. Similarly figure 7.38 and 7.39 show the map of the points that the end effector can reach while its frame is respectively rotated 90° around the X₀ and Y₀ (base frame) axis. The workspace is further limited imposing the instrument to slide inside the trocar and to avoid the obstacles along its path, this kind of constraints are addressed in Section 7.2.5. From the graphs it is possible to notice that not all the singular points lie on the boundary of the workspace; some singularities are inside the workspace.

END EFFECTOR Z // TO BASE Z₀
WORKSPACE SINGULARITIES WORKSP - SING

L₁= 50 mm, L₂= 15 mm, L₃= 36 mm, L₄= 39.5 mm, 0° ≤ θ₁ < 180°,
-90° ≤ θ₂ < 90°, 0° ≤ θ₃ < 180°, -180° ≤ θ₄ < 180°, -90° ≤ θ₅ < 90°, -180° ≤ θ₆ < 180°

*Figure 7.37 – Full mobility robotic tool: end effector parallel to Z₀*
Implementation and system integration

Figure 7.38 – Full mobility robotic tool: end effector parallel to $X_0$

END EFFECTOR $Z$
// TO BASE $X_0$

WORKSPACE
SINGULARITIES
WORKSP - SING

$L_1 = 50$ mm
$L_2 = 15$ mm
$L_3 = 36$ mm
$L_4 = 39.5$ mm

$0^\circ \leq \theta_1 < 180^\circ$
$-90^\circ \leq \theta_2 < 90^\circ$
$0^\circ \leq \theta_3 < 180^\circ$
$-180^\circ \leq \theta_4 < 180^\circ$
$-90^\circ \leq \theta_5 < 90^\circ$
$-180^\circ \leq \theta_6 < 180^\circ$

Figure 7.39 – Full mobility robotic tool: end effector parallel to $Y_0$

END EFFECTOR $Z$
// TO BASE $Y_0$

WORKSPACE
SINGULARITIES
WORKSP - SING

$L_1 = 50$ mm
$L_2 = 15$ mm
$L_3 = 36$ mm
$L_4 = 39.5$ mm

$0^\circ \leq \theta_1 < 180^\circ$
$-90^\circ \leq \theta_2 < 90^\circ$
$0^\circ \leq \theta_3 < 180^\circ$
$-180^\circ \leq \theta_4 < 180^\circ$
$-90^\circ \leq \theta_5 < 90^\circ$
$-180^\circ \leq \theta_6 < 180^\circ$
7.2.3 – Backward kinematics

The terms included in the link transformation used for the forward kinematics are non-linear respect to the mini-arm joint coordinates \((\theta_1, \theta_2, \theta_3, \theta_4, \theta_5 \text{ and } \theta_6)\). There are at least two solving strategies of the backward kinematics problem; closed form solutions and numerical solutions. Closed form solutions are guaranteed for two classes of robot architectures: robots with any free translational joints and robots having 6 DoF in which 3 consecutive axes intersect at a point (Pieper condition). These are decoupled robot architectures that can reduce the system made by 6 non-linear algebraic equations to a lower order subsystem (i.e. 3rd order) for which closed form is guaranteed.

For the robotic surgical instrument the Pieper’s condition applies (the last three joints intersect at a spherical center of rotation \(C\)) and a geometrical method, reduction to polynomial method and Pieper’s method can be used to generate closed form solutions (Craig86).

**Reduction to polynomial method**

The forward kinematics equations of the surgery mini-arm are transcendental. These equations can be converted into polynomial equations using the following substitutions:

\[
\begin{align*}
    u &= \tan \frac{\varphi}{2}, \\
    \cos \varphi &= \frac{1-u^2}{1+u^2}, \\
    \sin \varphi &= \frac{2u}{1+u^2}
\end{align*}
\]

For example the coordinate \(x\) of the end effector can be rewritten as:
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The equation is difficult to solve. This expression can be further simplified, but the result is still complex to handle (Appendix C). For this reason it has been chosen to try to solve the inverse kinematics with a different method.

**Pieper's method**

The backward kinematics of the full mobility mini-arm can be solved using the Pieper’s closed form method (Fig. 7.12, Craig86). With reference to the DH parameters of figure 7.19, the point intersection of the last three joint axes if given by:

\[
\begin{align*}
\mathbf{P}_{\text{ORG}} &= \mathbf{T}_{12} \mathbf{T}_{23} \mathbf{P}_{\text{ORG}} \\
\mathbf{P}_{\text{ORG}} &= \mathbf{T}_{12} \mathbf{T}_{23} \mathbf{P}_{\text{ORG}} = \begin{bmatrix}
a_3 \\
d_{3} \alpha_{3} \\
1
\end{bmatrix} = \begin{bmatrix}
\mathbf{T}(\vartheta_3) \mathbf{T}(\vartheta_2) \mathbf{T}(\vartheta_1)
\end{bmatrix} \begin{bmatrix}
a_3 \\
d_{3} \alpha_{3} \\
1
\end{bmatrix}
\end{align*}
\]

The previous formula can be rewritten:

\[
\begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
1
\end{bmatrix} = \begin{bmatrix}
a_3 \\
d_{3} \alpha_{3} \\
1
\end{bmatrix}
\]

and

\[
\begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
1
\end{bmatrix} = \begin{bmatrix}
a_3 \alpha_{3} + d_{3} \alpha_{3} s_{3} + a_3 = L_{3} s \vartheta_3 + L_3 \\
a_3 \alpha_{3} s_{3} - d_{3} \alpha_{3} c_{3} c_{3} - d_{3} \alpha_{3} c_{3} - d_{3} \alpha_{3} = 0 \\
a_3 \alpha_{3} s_{3} - d_{3} \alpha_{3} s_{3} c_{3} + d_{3} \alpha_{3} c_{3} c_{3} - d_{3} \alpha_{3} = L_{3} c \vartheta_3
\end{bmatrix}
\]

Doing the substitutions, the coordinates of the axes intersection can be written as:

\[
\begin{align*}
\mathbf{P}_{\text{ORG}} &= \mathbf{T}_{12} \mathbf{T}_{23} \mathbf{P}_{\text{ORG}} \\
\mathbf{P}_{\text{ORG}} &= \mathbf{T}_{12} \mathbf{T}_{23} \mathbf{P}_{\text{ORG}} = \begin{bmatrix}
a_3 \\
d_{3} \alpha_{3} \\
1
\end{bmatrix} = \begin{bmatrix}
\mathbf{T}(\vartheta_3) \mathbf{T}(\vartheta_2) \mathbf{T}(\vartheta_1)
\end{bmatrix} \begin{bmatrix}
a_3 \\
d_{3} \alpha_{3} \\
1
\end{bmatrix}
\end{align*}
\]
\[ \mathbf{p}_{\text{org}} = \begin{bmatrix} c_i g_1 - s_i g_2 \\ c_i g_1 + c_i g_2 \\ g_3 \\ 1 \end{bmatrix} \]

where

\[ g_1 = c_i f_1 - s_i f_2 + a_1 = L_s \theta_c \cos \theta_1 + L_c \theta_4 + L_4 \]

\[ g_2 = s_i c \alpha_1 f_1 + c_i c \alpha_1 f_2 - s \alpha_1 f_3 - d \alpha_1 = L_s \theta_9 s \theta_4 + L_2 s \theta_2 \]

\[ g_3 = s_i s \alpha_1 f_1 + c_i s \alpha_1 f_2 + c \alpha_1 f_1 - d \alpha_1 = L_s \theta_9 \]

The magnitude squared of \( \mathbf{p}_{\text{org}} \) can be written as:

\[ r = g_1^2 + g_2^2 + g_3^2 \]

Now, we study the system of equations formed by \( r \) and the coordinate \( z \) of the axes of intersection:

\[ r = (k_i c_i + k_s s_i) 2a_i + k_3 \quad \text{where} \quad k_i = f_i \]

\[ z = (k_i s_i + k_s c_i) s \alpha_4 + k_4 \quad \text{where} \quad k_i = f_i^2 + f_2^2 + f_3^2 + a_i^2 + d_i^2 + 2d_i f_3 \]

or, specifically:

\[ r = L_1^2 + L_2^2 + L_3^2 + 2L_1 L_2 s \theta_4 + 2L_1 L_3 c \theta_4 s \theta_9 + 2L_2 L_3 c \theta_2 \]

\[ z = L_3 c \theta_9 \]

The previous equation is useful because dependence on \( \theta_1 \) has been eliminated and dependence on \( \theta_2 \) takes a simple form. For the surgical instrument \( \alpha_1 = 0 \) then \( z = k_4 \).

After substituting a quadratic equation arises that, using the reduction to polynomial method, can be directly solved for \( \theta_4 \). Using the system of equation already introduced, \( \theta_1 \) and \( \theta_2 \) can be computed. Finally, the angles \( \theta_4, \theta_5 \) and \( \theta_6 \) can be solved for a set of approximately defined Euler angles (Craig86).

**Numerical method**

For robots that do not have decoupled geometries, a closed form solution may not exist and one has to resort to numerical and iterative procedures.
Numerical solutions to solve the inverse kinematic problem represented by \( m \) equations in \( n \) unknowns start with an initial estimate for the \( n \) unknowns and compute the error caused by this inaccurate estimate. The estimate is then iteratively modified to reduce the error.

Three important requirements for the numerical algorithm are:

- a priori conditions for convergence
- insensitivity to initial estimates
- provision for multiple solutions

The most common methods are based on the Newton-Raphson approach (Goldenberg85). Inverse kinematics solutions of a reconfigurable robot system built upon a collection of standardized modules is difficult to obtain because of its varying configuration. The formulation of a generic numerical inverse kinematics model and automatic generation of the model for arbitrary robot geometry, including serial type geometry, including both revolute and prismatic types of joints, may be given and the inverse kinematics model obtained. The backward kinematics of the redundant instrument has been computed numerically. The method adopted is described in Section 7.2.4.

### 7.2.4 – Robot dynamics

The equation of motion for the robot with forces acting on the gripper can be written as:

\[
M(q)\ddot{q} + f(q, \dot{q}) + g(q) - Bu - W(q)\lambda = 0
\]

with \( q = (q_1, q_2, q_3, \ldots, q_m) \),

\( u = (u_1, u_2, u_3, \ldots, u_m) \in \mathbb{R}^m \) is the actuation vector.
\( M \in \mathbb{R}^{m \times m} \) is the inertia matrix
\( B \in \mathbb{R}^{m \times m} \) is the control matrix
\( f \in \mathbb{R}^m \) is a vector containing the Coriolis and centrifugal forces
\( g \in \mathbb{R}^m \) is a vector containing the gravitational forces
\( \lambda \in \mathbb{R}^6 \) contains all contact forces and torques acting on the gripper
\( W \in \mathbb{R}^{6 \times 6} \) is the gripper environment interaction matrix

The previous equation represents open loop dynamics in the case of \( u = 0 \). In this case the instrument behaves as a passive kinematic chain and dynamic simulation shows its motion when generalized forces \( \lambda \) are applied to the gripper.

Different linear control algorithms can be considered by writing the corresponding control matrix \( B \).

Assuming the robot be controlled by independent PD joint controllers, one for each joint:

\[
u_i = -K_p(q_i - q_{id}) - K_D(\dot{q}_i - \dot{q}_{id})\]

There are several tools that enable to implement dynamic model and control of robots; two examples are Open Dynamic Engine (ODE) and Webots 4 (ODE05, Webots05).

The problems of the direct and inverse dynamics of the general redundant mini-arm have been addressed numerically exploiting the potentialities of the Open Dynamic Engine (ODE). ODE is a fast, free and open source, 3D engine consisting of a set of libraries written in C++ that can be used to simulate complex physical systems (Battista04, Appendix D). Each body is defined by at least the following attributes; mass, real geometry and representative geometry. The bodies can be linked each other by joints or motors. A parametric simulation environment containing the proposed mini-
Implementation and system integration

arm and a virtual operative scenario has been implemented (Appendix E). The simulation runs numerically. Inertia, forces, gravity, friction, contacts and collisions are considered. A simplified model of the whole instrument is produced in order to enhance the simulation speed.

To enhance the computation speed, while the screen displays the real geometry of the bodies, generally, a simplified representative geometry model is used to calculate the contacts. ODE is fast; it allows to simulate scenes with more than 50 bodies in (about) real time. The user, while the simulation runs, can interact with the keyword; some keys can be used, for example, to control the bodies or to modify the position of the cameras for a better visualization. To enhance the simulation speed, a simplified model of the whole instrument is produced.

The simulation environment (450 lines of code), implemented to simulate and control the surgical instrument, is now described (Appendix E). The surgery mini-arm (yellow worm), is winded on the mini-arm dispencer (red wheel). The blue door represents the trocar (Fig. 7.40).

Figure 7.40 – Simulation environment
A mass is assigned to each body. Modules are joined each over by spherical joints. A spherical joint links the wheel dispenser to the mini-arm. The rotation spans of the joints are considered and the self-collision configurations are detected and eliminated.

Collision detection is enabled between each module and the mini-arm body, and between each non-adjacent module. This routine considers the interaction between non-adjacent links and between the links and the virtual environment. Collision detection between subsequent modules can be implemented only adopting representation B (Fig. 7.41).

The mini-arm is almost blind; the proximity sensors embedded in each module consider and feel only the organs close to the mini-arm body. Collision detection is enabled between each mini-arm module and the environment and between each couple of non-adjacent modules. The mini-arm feels the environment by means of the proximity sensors embedded in the modules. These sensors feel only the organs very close to the mini-arm body; the mini-arm advances blind until any organ becomes close to some portion of its external surface. The threshold of the distance between organs and instrument body, for example, can vary from 15 to 2 mm.
The control interface needs to be as clear and friendly as possible. Surgeons need to easily position and orient the end effector (backward dynamics), without having to take care about possible contacts between the instruments and the organs. The control proposed can automatically manage contacts (Appendix E). The desired position of the end effector, directly chosen by the user (mouse interface), is reached only if the described contact conditions are satisfied. Whether the problem is geometrically “impossible”, the control places the whole mini-arm in the position that allows the end effector to be closest to the desired posture.

A hierarchy of constraints applies to the mini-arm.

**Condition 1)** Limited torque is applied to the mini-arm dispenser wheel (low priority constraint).

**Condition 2)** High contact forces originated when the mini-arm gets close to an object, e.g. an organ (high priority constraints, represented by the symbol star in Fig. 7.42 and 7.43).

**Condition 3)** A force and a torque, proportional to the difference between the actual and desired posture of the end effector, are applied to the instrument tip (medium priority constraint). The instrument is virtually pulled out from the dispenser.

**Condition 4)** A force and a torque, chosen by the surgeon, are exerted from the instrument tip on the patient’s body (medium priority constraint).

The mini-arm can operate following two modes; approaching mode and manipulation mode. During the approach **Condition 1, Condition 2** and **Condition 3** are imposed to solve the inverse kinematics and the insertion problem.

**Condition 1** tends to pull the mini-arm out of the dispenser like a chain, providing that
only a minimum number of modules enters into the patient. Condition 3 is weaker than Condition 2; even if the surgeon desires to reach positions geometrically impossible, the instrument is not allowed to penetrate the organs. Organs having random shape have been inserted into the ODE simulation environment.

Figure 7.42 shows an example of simulation output. First the surgeon chooses, using a mouse interface, the final posture (symbol “X”), that the end effector should reach (Fig 42.A). After, the best path to reach the target (symbol “O”) is iteratively suggested (Fig. 42.B and 42.C). The surgeon can adopt different criteria to select the best mini-arm path; for example, instead of choosing to reach the target along the shortest path, it could be interested to follow a longer path ensuring that a real delicate organ (organ “2”) is not touched. 

Figure 7.42 – Path planning strategy
During the manipulation, the tip pulling force and torque (Condition 3) and the dispenser torque (Condition 1) are removed from the mini-arm; the surgeon can manipulate the reached organ applying forces and torques on it (Condition 4) or activating instruments (e.g. grippers, scalpels etc.). The ODE function "Amotor", can be used to compute the correct motor torques required to drive the mini-arm (Fig. 7.43).

The proposed control uses only proximity/tactile sensor feedback: future implementations of the control will include a more complete sensors fusion (Fig. 7.44).

Surgeons could, for example, drive the mini-arm using a “2D+1D” control (Fig. 7.45). The user can ask the mini-arm to move forward or backward (1D). Other commands allow the tip of the mini-arm to move up, down, left and right, by respect to the plane.
normal to the mini-arm last module.

![Figure 7.45 – 21+1D control](image)

Thanks to the control algorithm developed, the surgeon can follow the operation, taking care only of the final instrument, while the body of the mini-arm avoids automatically any vital organ, localised by the proximity sensors positioned along the mini-arm. Several tests have shown that the control strategy is effective; simulation parameters have still to be set up to ensure the control stability.
Implementation and system integration
A new articulated mini-arm for MIS has been conceived, designed, realised and validated. It is ready for early tests in vivo (on a pork).

At the end of the three years way the research project has been successfully closed and some interesting results have been reached. They are summarised and discussed in this chapter. While going deeply into the new subjects, that time by time were faced, the research panorama grew and showed new perspectives, new ideas and issues that couldn’t be faced in the PhD thesis are also outlined in the chapter.

8.1 – The adopted methodology

The project was faced as an industrial project with more or less specified requirements, as reported in the first chapter, not neglecting cost constraints, nerveless opening the mind to new technologies, materials, sensors-motors and control solutions following an interdisciplinary approach.

We consider key of success to have involved, at every step, in the design feedback, the
Conclusion and further developments

surgeons and end-users: their contribution was precious. The ex-post evaluation of the results obtained by the proposed MIRS applications will give extremely useful feedback for further improvement of the instrument and for its exploitation with wide social acceptance and satisfaction.

Now that the mini-arm has been realised, it is our concern to compare its characteristics to the given requirements one by one, discussing the reasons of not complete fulfilment, if the case. We think that even the discussion of failure is fruitful and adds value to the thesis addressing future researches.

8.1.1 – High mobility and dexterous workspace

The modular mini-arm fully satisfies this requirement. Modularity allows the configuration of the instrument to be suitable for different kind of surgical operations. Focusing on the heart surgery and more precisely on Coronary Artery Bypass Grafting a redundant instrument has been realised, that allows complete mobility: 6 DoF in the workspace also in presence of physical constraints that kill one DoF.

The proposed instrument architecture that collects the redundant mini-arm rolled up within a suitable box allows the surgeon to use the right number of modules and DoFs for the given task. For his choices the surgeon tools on workspace simulation and singularity analysis that can be run “a priory” the surgical procedure on a virtual body.

The developed tools are based on the mathematical model and do not consider problems due to the physical embodiment such as cabling arrangement.

The workspace is shared with other mini-arms collaborating to the same surgical procedure either for video servoing teleoperation either for performing cooperative tasks. They are mobile objects within the scene to be carefully considered.
8.1.2 – Miniaturisation

The required dimensions has been satisfied. The actual instrument has maximum diameter 10 mm. This dimension has been determined by the actuators embedded into each module. In fact, the adopted philosophy of modularity imposed that each module behaves as an holon, equipped with its sensors and actuators. So, being excluded, in principle, the relocation of actuation, the sizing of the modules was due to the mini-motors and gears focused on the market and to the joints structural dimensioning oriented to the forces and moments needed by the environment interaction.

Without varying the modularity concept, further miniaturisation will be possible as far as further actuation components will be reached. In any case, accurate re-shaping of joints and finite element analysis, together with new selected material properties, will be taken into account.

From the experience acquired in these years, we note that whenever we move towards smaller and smaller scale, it is better and better to resort to new intelligent, alive materials for actuation. In this way the same material plays both a structural and an actuation role. This approach has been applied for grippers design, as described in chapter 6 and seems to offer new interesting solutions; some problems still remain about the needs of efficient cooling systems.

8.1.3 – Versatility

Versatility requirements referred to the adaptability of the instrument to different surgical procedures and to the re-tooling of the instrument for different tasks within the same procedure.

The adoption of the described modular instrument allows the complete fulfilment of
this requirement and open new prospective about families of modular tools and standard interfaces. An advantage of the modular mini-arm is its open reconfigurability obtained by assembling a number of modules identical or different in a given sequence, in function of the surgical task mobility, workspaces and performance specifications. For each obtained architecture of the mini-arm, the workspace position and/or force control level has to be defined and algorithms written following the same approach described in chapter 7 for the mini-arm architecture optimised for heart CABC procedures.

With reference to the instrument adaptability in short, the end-effector tool changing mechatronic device with easy assembly and disassembly functions demonstrates the real feasibility of the general concept.

8.1.4 – Modularity

During the different research work stages and progression modularity was considered as a design philosophy and tool, useful to reach and satisfy life-cycle requirements, such as maintainability and re-usability, more than an instrument specification, by itself.

Modularity, in fact, offers numerous advantages at design, realization and use level. Designer can concentrate on the module optimizing its characteristics. Realization of identical modules reduces costs. In case of failure, a module can be easily replaced with a new one in very short time in a plug and play fashion.

On the other side, in general, modularity introduces some drawbacks by limiting the designer creativity and reducing the power efficiency. In fact the designer, after a top-down approach with the aim to define the number of different modules and their characteristics, concentrates on the selected modules features without any feedback on
Chapter 8

their selection. The use of the same selected modules in any segment of the open kinematic chain of the mini-arm should use badly the power because the same actuation power is assigned to the first, more solicited, module of the chain, and to the last segments that have lower static and dynamic loads.

With reference to the surgical procedures world, these main drawbacks, typical of modularity, seemed to be well balanced and overcome by the strong advantages.

8.1.5 – Operative performances

Accuracy requirements oriented the design of the realization of the modules, in particular of the joints, and the selection of the motion components; mainly of the minimotor resolution and reducers characteristics. The 03A Smoovy minimotor coupled with a three stages planetary gearbox (reduction 1:125) has been selected. The angular position of the links is measured by a no-contact magnetic sensor 2SA-10 from Sentron (Appendix A). The mechatronic interfaces between the modules were very accurately designed and realized to avoid backlashes. Great attention has been paid to the module parameters influencing the accuracy, considering that the serial kinematic chain of the arm amplifies rotary joint errors. The preliminary tests of the instrument showed an acceptable behaviour in terms of accuracy and stiffness.

It must be noted that error compensation software modules based on the kinematic model and suitable calibration procedures should improve the instrument performances. Other arrangements and compensations may be done through a good use of teleoperation based on the visual feedback. Visual feedback may be improved by the intelligent use of a mini-arm supported camera and fast effective scene reconstruction algorithms.
Force feedback has not yet been implemented on the prototype but some ideas have been proposed and studied for further developments. Obstacle avoidance is very critical for safety reasons.

The early prototype (Fig 8.1) is not equipped with proximity sensors and their delicate task is left to the surgeon ability and on the training cycles performed on virtual body in order to define safe mini-arm trajectories.

<table>
<thead>
<tr>
<th>Module</th>
<th>Material</th>
<th>PEEK aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Couple</td>
<td>5.8 mNm</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>72 °/s</td>
<td></td>
</tr>
<tr>
<td>Spam</td>
<td>± 104°</td>
<td></td>
</tr>
<tr>
<td>External diameter</td>
<td>10 mm</td>
<td></td>
</tr>
<tr>
<td>Mini-arm</td>
<td>Length</td>
<td>120 mm</td>
</tr>
<tr>
<td></td>
<td>N° of DoF</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Weight</td>
<td>20 g</td>
</tr>
<tr>
<td></td>
<td>Sewing operation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clamp: clamping force</td>
<td>20 N</td>
</tr>
<tr>
<td></td>
<td>Nail: piercing force</td>
<td>0.5 N</td>
</tr>
<tr>
<td></td>
<td>Wire: stretch</td>
<td>1.0 N</td>
</tr>
</tbody>
</table>

**Figure 8.1 – Mini-arm characteristics**

Kinematic performances such as velocity and acceleration of the end effector concur to shorten the surgical procedure duration with benefit to the patient but they cannot be stressed because could make worse the accuracy and tire the teleoperator.

**8.1.6 – Safety**

The mini-arm is intrinsically safe; the design is oriented to guarantee safety in all the phases of the instrument life cycle. The existing standards about medical devices: 93/42/EEC and 90/385/EEC were considered. Figure 8.2 shows the flowchart for the conformity assessment procedures provided for in Directive 93/42/EEC.
At the level of hardware and software components, the main choices influenced by the safety needs and regulations are shortly recalled in the following. The actuation is realised with commercial brushless mini-motors whose power is limited to 0.4 W. The motor nominal tension is 3.3 V. In order to limit the motor velocity, a multistage reduction gear is mounted on each motor output shaft with high reduction ratio.

Watch dog circuit to verify and alert if some software functions are no more right has not been jet implemented in the prototype but it is foreseen for the final product in order to manage security from a software point of view.

Very easy understandable monitoring of the procedure progression with simple vision/acoustic blanking alarm signals in case of components failure have to be implemented.
Conclusion and further developments

Automatic stop and emergency procedure have been considered and discussed but are not yet implemented.

Internal cabling should be preferred but in our prototype, that uses market components and miniaturized traditional motors it was impossible to realize. So it is required to cover the mini-arm with a sterile sleeve.

### 8.1.7 – Redundancy

A mini-arm redundant in terms of internal mobility has been proposed. Redundancy assures the workspace complete mobility of the arm even in presence of constraints. The related complexity of the kinematics and control level is balanced by the good mobility characteristics that comply with the given specifications.

Other kinds of redundancy related to the circuits and information duplication are very important for safety reasons but, at the actual stage of development of the instrument, are not yet been faced.

### 8.1.8 – Body compatibility

The mini-arm is realised in PEEK and aluminium. PEEK has been selected for its good mechanical and electrical isolation properties. Furthermore PEEK is a polymer tolerated by human body.

The prototype will be covered with a sterile sleeve in order to comply with clinical constraints.

### 8.1.9 – Control

The mini-arm was deeply analysed and kinematic mathematical models have been derived, discussed and tested by simulation. These modules are proposed to be used within the new decision support tools for the teleoperating surgeon and the online
control systems.

These model based tools are not yet realised but their effectiveness, tested in simulation, seems good. From the cooperative work performed, many useful indications about the surgeon/mini-arm interface have been pointed out. Suitable simplification of the interface will give easy monitoring and information representation allowing intuitive and fast interpretation and reaction from the surgeon.

The mini-arm functional modelling effort opens new perspectives about control systems and logics able to improve the surgical instrument performances. Non linearity typical of the serial kinematics mini-arms could be compensated completely or partially at level of gravitational, Coriolis and centrifugal terms. The reference models have been defined and tested but their implementation into realtime control logics has to be performed.

Dame considerations hold for forces reflection to the surgeon and hybrid position-force or compliance control of the mini-arm.

### 8.1.10 – Further developments

Main aim and achievement were the analysis design and realisation of a new surgical instrument oriented to the specifications described in chapter 1. A brief discussion about the obtained results is given in the previous section. In the same sections some considerations are given about the problems that we have not solved till now. They open new perspectives for the near future.

### 8.2 – Acknowledgements and publications

During the three years of my PhD I had a lot of fun; I had the possibility to explore a field of research for me new and exciting. Surgery robotics is growing fast, is open to innovation and deeply related with human needs. I collaborated and had contacts with
Conclusion and further developments

people from Russia, Europe and USA; all the team was friendly, professional and deep interested in the subject. A warm thanks to everyone (Fig. 8.3).

The modules torques are compatible with the sewing needs. The solutions and ideas presented need to be further developed and enhanced to become real industrial products: areas of investigation and margins of improvement are wide.

State of art

Arm design

Kinematics and Control

Figure 8.3 – Researchers involved
The increase of the overall mini-arm stiffness and accuracy is crucial. The advent of new smart materials and actuators will further widen the design possibilities.

Part of the material included in the thesis has been presented in conferences and published in international journals:


F. Cepolina, D. Sallé, P. Bidaud “Innovative instruments for minimally invasive coronary artery bypass grafting”, IEEE Transactions on Biomedical Engineering (under review) 2005

F. Cepolina, M. Zoppi “Snail surgeon: a new robotic system for minimally invasive surgery”, 5th International Workshop on Robot Motion and Control RoMoCo’05 (under review) 2005
Appendix A

Commercial components

PEEK material       A.2
Smoovy motor         A.4
Sentron sensor       A.5
SMA wire actuation   A.9
Quadrant EPP Ketron® PEEK 1000 Polyetheretherketone, unfilled, extruded

Subcategory: Polyetheretherketone (PEEK); Polyketone; Polymer; Thermoplastic

Material Notes:
Ketron PEEK grades offer chemical and hydrolysis resistance similar to PPS, but can operate at higher temperatures. Unreinforced, extruded Ketron PEEK offers good wear resistance and can be used continuously to 480°F (250°C). It can also be used in hot water or steam without permanent loss in physical properties. For hostile environments, PEEK is a high strength alternative to fluoropolymers. PEEK carries a V-O flammability rating and exhibits very low smoke and toxic gas emission when exposed to flame.

Data provided by Quadrant Engineering Plastic Products (formerly DSM EPP).

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Metric</th>
<th>English</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.31 g/cc</td>
<td>0.0473 lb/in³</td>
<td>ASTM D792</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>0.1 %</td>
<td>0.1 %</td>
<td>24 hour immersion; ASTM D570</td>
</tr>
<tr>
<td>Moisture Absorption at Equilibrium</td>
<td>0.1 %</td>
<td>0.1 %</td>
<td>Water Vapor Regained</td>
</tr>
<tr>
<td>Water Absorption at Saturation</td>
<td>0.5 %</td>
<td>0.5 %</td>
<td>Immersion; ASTM D570</td>
</tr>
<tr>
<td>Outgassing - Total Mass Loss</td>
<td>0.3 %</td>
<td>0.3 %</td>
<td></td>
</tr>
<tr>
<td>Collected Volatile Condensable Material</td>
<td>0 %</td>
<td>0 %</td>
<td></td>
</tr>
</tbody>
</table>

Chemical Properties

| Ionic Impurities - Na (Sodium) | 480 ppm | 480 ppm |
| Ionic Impurities - K (Potassium) | 0.2 ppm | 0.2 ppm |
| Ionic Impurities - Fe (Iron) | 0.4 ppm | 0.4 ppm |

Mechanical Properties

| Hardness, Rockwell M | 100 | 100 | ASTM D785 |
| Hardness, Rockwell R | 126 | 126 | ASTM D785 |
| Hardness, Shore D | 85 | 85 | ASTM D2240 |
| Tensile Strength, Ultimate | 110 MPa | 16000 psi | ASTM D638 |
| Elongation at Break | 20 % | 20 % | ASTM D638 |
| Tensile Modulus | 3.45 GPa | 500 ksi | ASTM D638 |
| Flexural Modulus | 4.14 GPa | 600 ksi | ASTM D790 |
| Flexural Yield Strength | 172 MPa | 25000 psi | ASTM D790 |
| Compressive Yield Strength | 138 MPa | 20000 psi | 10% Deflection; ASTM D695 |
| Compressive Modulus | 3.45 GPa | 500 ksi | ASTM D695 |
| Machinability | 50 % | 50 % | QEPP 10 to 100 scale |
| Shear Strength | 55.2 MPa | 8000 psi | ASTM D732 |
| Coefficient of Friction | 0.4 | 0.4 | Dynamic; Dry vs. Steel; PTM55007 |
| K (wear) Factor | 375 | 375 | 10^-14 in^3/min/lb-ft-hr; PTM55007 |
| Limiting Pressure Velocity | 0.298 MPa-m/sec | 8500 psi-ft/min | PTM55007 |
| Izod Impact, Notched | 0.534 J/cm | 1 ft-lb/in | ASTM D256A |

Electrical Properties

| Surface Resistivity per Square | Min 1e+013 ohm | Min 1e+013 ohm | EOS/ESD S11.11 |
| Dielectric Constant | 3.3 | 3.3 | 1 MHz; ASTM D150(2) |
| Dielectric Strength | 18.9 kV/mm | 480 V/mil | Short Term; ASTM D149(2) |
| Dissipation Factor | 0.003 | 0.003 | 1 MHz; ASTM D150(2) |
Thermal Properties
CTE, linear 68°F 46.8 µin/m-°C 26 µin/in-°F ASTM E831 (TMA)
Thermal Conductivity 0.259 W/m-K 1.8 BTU-in/hr-ft²-°F
Melting Point 340 °C 644 °F ASTM D3418
Maximum Service Temperature, Air 249 °C 480 °F Continuous Service Without Load
Deflection Temperature at 1.8 MPa (264 psi) 160 °C 320 °F ASTM D648
Flammability, UL94 V-0 V-0 UL94

Descriptive Properties
Compliance - Canada AG Not Compliant
Compliance - Dairy 3A Compliant
Compliance - FDA Compliant
Compliance - NSF Not Compliant
Compliance - USDA Compliant
Compliance - USP Class VI Not Compliant
Service in Alcohols Acceptable
Service in Aliphatic Hydrocarbons Acceptable
Service in Aromatic Hydrocarbons Acceptable
Service in Chlorinated Solvents Acceptable
Service in Continuous Sunlight Limited
Service in Ethers Acceptable
Service in Inorganic Salt Solutions Acceptable
Service in Ketones Acceptable
Service in Steam Acceptable
Service in Strong Acids Limited
Service in Strong Alkalies Acceptable
Service in Weak Acids Acceptable
Service in Weak Alkalies Acceptable

http://www.matweb.com/search/SpecificMaterialPrint.asp?bassnum=P1SM12A
Appendix A

Planetary Gearheads

0.88 mNm

For combination with Brightless DC-Micromotors: O03A

### Series 03A

<table>
<thead>
<tr>
<th>Specification</th>
<th>O03A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing material</td>
<td>steel</td>
</tr>
<tr>
<td>Geartrain material</td>
<td>steel</td>
</tr>
<tr>
<td>Recommended max. input speed for:</td>
<td></td>
</tr>
<tr>
<td>continuous operation</td>
<td>15 000 rpm</td>
</tr>
<tr>
<td>Backlash, at no-load</td>
<td>0.2°</td>
</tr>
<tr>
<td>Bearings on output shaft</td>
<td>bronze</td>
</tr>
<tr>
<td>Shaft load, max.</td>
<td></td>
</tr>
<tr>
<td>radial (1.5 mm from mounting flange)</td>
<td>0.1 N</td>
</tr>
<tr>
<td>axial</td>
<td>0.2 N</td>
</tr>
<tr>
<td>Shaft press fit torque, max.</td>
<td>1 N</td>
</tr>
<tr>
<td>Shaft play (on bearing output)</td>
<td></td>
</tr>
<tr>
<td>radial</td>
<td>≤ 0.02 mm</td>
</tr>
<tr>
<td>axial</td>
<td>≤ 0.1 mm</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-20...+60°C</td>
</tr>
</tbody>
</table>

#### Specifications

<table>
<thead>
<tr>
<th>Reduction ratio (nominal)</th>
<th>Weight without motor</th>
<th>Output torque continuous operation</th>
<th>Output torque intermittent operation</th>
<th>Direction of rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>M max. 0.25 rpm</td>
<td>M max. 0.42 rpm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>0.60</td>
<td>1.32</td>
<td></td>
</tr>
</tbody>
</table>

Note: The Planetary Gearheads are only available in combination with the brashless DC-Servomotors Series O006...B.

Edition 10. 08. 2008

Specifications subject to change without notice.

www.tsu.huber.net

http://www.mpsag.com/pdf/mps_datenblaetter/03A/eG03A.pdf
Package: SOIC-8

Pin-out:

1. CO_OUT, common output
2. PC, programming clock
3. VDD, Supply voltage
4. Y_OUT, Y-channel analog output
5. X_OUT, X-channel analog output
6. PD, programming data
7. PV, programming voltage
8. GND, Supply common

Note 1: Used for factory programming

Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min.</th>
<th>Max.</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{SUP}$</td>
<td>Supply Voltage</td>
<td>0</td>
<td>6</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>Ambient Temperature</td>
<td>-40</td>
<td>+150</td>
<td>°C</td>
<td></td>
</tr>
</tbody>
</table>

Magnetic Input Conditions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min.</th>
<th>Max.</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{MAX}^{2}$</td>
<td>Max. Induction</td>
<td>&gt;1000</td>
<td></td>
<td>mT</td>
<td>Device saturates, but is not damaged</td>
</tr>
<tr>
<td>$D_{FC}$</td>
<td>Diameter of magnetic disk</td>
<td>0.2</td>
<td></td>
<td>mm</td>
<td>See Figure 5 for location of disk</td>
</tr>
<tr>
<td>$\omega$</td>
<td>angular speed</td>
<td>100'000</td>
<td></td>
<td>rpm</td>
<td></td>
</tr>
</tbody>
</table>

Note 2: At center of magnetic disc

Recommended Operating Conditions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{SUP}$</td>
<td>Supply Voltage</td>
<td>4.5</td>
<td>5</td>
<td>5.5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>$I_{OUT}$</td>
<td>Output Current</td>
<td>-1</td>
<td></td>
<td>1</td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td>$C_L$</td>
<td>Load Capacitance</td>
<td></td>
<td></td>
<td>1000</td>
<td>pF</td>
<td></td>
</tr>
<tr>
<td>$B^{3}$</td>
<td>Magnetic Field</td>
<td></td>
<td></td>
<td>80</td>
<td>mT</td>
<td></td>
</tr>
</tbody>
</table>

Note 3: At center of magnetic disc
### Electrical Characteristics

At $T=+40^\circ\text{C}$ to $150^\circ\text{C}$, $V_{\text{SUP}}=+5\text{V}$ to $5.5\text{V}$ if not otherwise specified.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
<th>Test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{SUP}}$</td>
<td>Supply Current</td>
<td>16</td>
<td>18</td>
<td>mA</td>
<td>$I_{\text{OUT}}=0\text{mA}$</td>
<td></td>
</tr>
<tr>
<td>CO_OUT</td>
<td>Common (reference) Output Voltage</td>
<td>$V_{\text{SUP}}/2$</td>
<td>$V_{\text{SUP}}/2$</td>
<td>$V_{\text{SUP}}/2$</td>
<td>$V_{\text{SUP}}+2\text{mV}$</td>
<td>$I_{\text{OUT}}=0\text{mA}$</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth: DC to</td>
<td>10</td>
<td>15</td>
<td>18</td>
<td>kHz</td>
<td></td>
</tr>
</tbody>
</table>

**Note 4:** Ratio metric (proportional to $V_{\text{SUP}}$)

### Analog Output-Characteristics

With $V_{\text{SUP}}=+5\text{V}$ and the temperature range $-40^\circ\text{C}$ to $150^\circ\text{C}$, if not otherwise specified.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
<th>Test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>Magnetic Sensitivity</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>V/T</td>
<td>$I_{\text{OUT}}=0\text{mA}$</td>
</tr>
<tr>
<td>$\Delta S/\Delta T$</td>
<td>Magnetic Sensitivity</td>
<td>-0.05</td>
<td>0.05</td>
<td>%/°C</td>
<td>$I_{\text{OUT}}=0\text{mA}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta S_x/\Delta S_y$</td>
<td>Magnetic Sensitivity</td>
<td>0</td>
<td>2</td>
<td>%</td>
<td>$I_{\text{OUT}}=0\text{mA}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta S_x-S_y$</td>
<td>Phase matching</td>
<td>-0.3</td>
<td>0.3</td>
<td>%</td>
<td>$I_{\text{OUT}}=0\text{mA}$</td>
<td></td>
</tr>
<tr>
<td>$V_{\text{off}}$</td>
<td>Offset Voltage</td>
<td>-10</td>
<td>0</td>
<td>10</td>
<td>mV</td>
<td>$B=0\text{T}^7)$</td>
</tr>
<tr>
<td>$\Delta V_{\text{off}}/\Delta T$</td>
<td>Offset Voltage</td>
<td>0</td>
<td>0.05</td>
<td>mV/°C</td>
<td>$B=0\text{T}^7)$</td>
<td></td>
</tr>
<tr>
<td>$B_{\text{FS}}^{7,8)}$</td>
<td>Full Scale Magnetic Field Range</td>
<td>45</td>
<td>45</td>
<td>mT</td>
<td>$B=0\text{T}^7)$</td>
<td></td>
</tr>
<tr>
<td>$B_{\text{L}}^{7,8}$</td>
<td>Linear Magnetic Field Range</td>
<td>40</td>
<td>40</td>
<td>mT</td>
<td>$B=0\text{T}^7)$</td>
<td></td>
</tr>
<tr>
<td>$N_{L}$</td>
<td>Non Linearity</td>
<td>0.1</td>
<td>0.2</td>
<td>%</td>
<td>For $B \leq B_{\text{L}}^{7,8}$)</td>
<td></td>
</tr>
<tr>
<td>$\Delta B_{\text{Noise}}^{7)}$</td>
<td>Input referred magnetic noise spectrum density (RMS)</td>
<td>750</td>
<td>$nT/\sqrt{Hz}$</td>
<td>$B_{\text{W}}=1\text{Hz}$ to $10\text{kHz}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_{\text{OUT}}^{\text{max}}$</td>
<td>Max. full scale output voltage</td>
<td>$5%V_{\text{SUP}}$</td>
<td>$95%V_{\text{SUP}}$</td>
<td>$V$</td>
<td>$</td>
<td>B</td>
</tr>
<tr>
<td>$Y_{\text{OUT}}^{\text{max}}$</td>
<td>Max. full scale output voltage</td>
<td>$5%V_{\text{SUP}}$</td>
<td>$95%V_{\text{SUP}}$</td>
<td>$V$</td>
<td>$</td>
<td>B</td>
</tr>
<tr>
<td>$H_{\text{y,max}}$</td>
<td>Maximum Hysteresis</td>
<td>0.03</td>
<td>%</td>
<td>$B_{\text{FS}}$</td>
<td>$</td>
<td>B</td>
</tr>
</tbody>
</table>

**Note 5:** When the analog output pins $X_{\text{OUT}}$ and $Y_{\text{OUT}}$ are used

**Note 6:** Ratio metric (proportional to $V_{\text{SUP}}$)

**Note 7:** At center of magnetic disk

**Note 8:** The 2SA-10 can also be ordered with Sensitivity of $25\text{V/T}$ for $B_{\text{FS}}=50\text{mT}$ and $B_{\text{FS}}=80\text{mT}$
Package dimensions SOIC-8

Dimension and Pads 2SA-10 in dice form
(all dimensions in µm)

Fig. 3  Package dimensions and magnetic sensitive directions

Fig. 4  2SA-10 dimensions of dice
Applications

The unique integrated two-axis Hall-sensor offers a rugged, low cost solution for any rotational reference detection. Application examples are found in contactless angular sensors and encoders, in rotational switches, in brushless DC motors and in joysticks.

The 2SA-10 is applied in a way very similar to magnetoresistive GMR and AMR angular sensors by sensing the rotation of a magnetic field component parallel with the chip. However, the full integration of magnetic field sensor and programmable signal conditioning circuit of the 2SA-10 offers an exceptional cost effectiveness.

Sentron’s 2SA-10 combines the advantage of a miniaturized angular sensor solution and simultaneously higher product performance and reliability. The features of high sensitivity, low offset and low temperature drift meets even the most demanding requirements across many industries.

Absolute Angle Sensor

The 2SA-10 is positioned under a rotating magnet mounted at the shaft end of a rotating axis. The magnet is magnetized diametrically, so that by rotating the shaft the field through the sensor also rotates. The generated voltages Vx and Vy of the 2SA-10 represent the sine and cosine of the magnetic field direction. Even though the signal amplitudes depend upon the vertical distance between sensor and magnet, the angle information, which is calculated by the ratio of Vx and Vy is not depending on this value. In this manner the angle sensor is very robust towards sensitivity temperature drift, magnet temperature drift and ageing effects as well as assembly tolerances.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Flexinol Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
</tr>
<tr>
<td>Wire Diameter (µm)</td>
<td>25 30 45 50 60 75 100 125 150 180 200 250 300 375</td>
</tr>
<tr>
<td>Minimum Braid Radius (mm)</td>
<td>1.3 1.85 2.5 3.75 5.0 6.25 7.5 10.0 12.5 15.0 18.75</td>
</tr>
<tr>
<td>Cross-sectional Area (µm²)</td>
<td>40 107.5 150 190 450 780 1270 17200 31200 65100 70500 101050</td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
</tr>
<tr>
<td>Linear Resistance (Ω/m)</td>
<td>1.77 0.86 0.50 0.20 0.10 0.07 0.05 0.04 0.03 0.02 0.01 0.005 0.005</td>
</tr>
<tr>
<td>Recommended Current (mA)</td>
<td>20 50 100 150 200 250 300 400 500 600 800 1000 1500</td>
</tr>
<tr>
<td>Recommended Power (W/m)</td>
<td>0.71 0.78 1.28 2.80 6.86 6.86 8.00 12.0 20.0 30.0 30.0 60.0 100.0</td>
</tr>
<tr>
<td><strong>Strength</strong></td>
<td></td>
</tr>
<tr>
<td>Max. Recovery Weight @ 600 MPa (g)</td>
<td>29 65 117 250 468 736 1056 1800 2500 3200 4200 6600</td>
</tr>
<tr>
<td>Rec. Recovery Weight @ 190 MPa (g)</td>
<td>7 20 35 50 80 150 290 530 950 1500 2200</td>
</tr>
<tr>
<td>Rec. Deformation Weight @ 35 MPa (g)</td>
<td>2 4 8 14 26 45 62 90 110 172 265 303</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td></td>
</tr>
<tr>
<td>Typical Contraction Speed (sec)</td>
<td>1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0</td>
</tr>
<tr>
<td>LT Relaxation Speed (sec)</td>
<td>0.15 0.25 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3</td>
</tr>
<tr>
<td>HT Alloy Thermal Cycle Rate (cyc/min)</td>
<td>52 68 84 100 133 200 333 400 500 666 800 1000 1500</td>
</tr>
<tr>
<td>HT Alloy Relaxation Speed (sec)</td>
<td>na. 0.09 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1</td>
</tr>
<tr>
<td>HT Alloy Thermal Cycle Rate (cyc/min)</td>
<td>na. 55 66 77 88 99 110 121 132 143 154 165 186 207</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>LT alloy TF alloy</td>
</tr>
<tr>
<td>Activation Start Temp. (°C)</td>
<td>68 88</td>
</tr>
<tr>
<td>Activation Finish Temp. (°C)</td>
<td>78 98</td>
</tr>
<tr>
<td>Relaxation Start Temp. (°C)</td>
<td>52 72</td>
</tr>
<tr>
<td>Relaxation Finish Temp. (°C)</td>
<td>44 64</td>
</tr>
<tr>
<td>Annealing Temp. (°C)</td>
<td>300 300</td>
</tr>
<tr>
<td>Melting Temp. (°C)</td>
<td>1300 1300</td>
</tr>
<tr>
<td>Specific Heat (cal/g°C)</td>
<td>0.077 0.077</td>
</tr>
<tr>
<td>Heat Capacity (Joule/g)</td>
<td>0.32 0.32</td>
</tr>
<tr>
<td>Latent Heat (Joule/g)</td>
<td>24.2 24.2</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td></td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>6.45</td>
</tr>
<tr>
<td>Maximum Recovery Force (MPa)</td>
<td>600 (~63 tons / in²)</td>
</tr>
<tr>
<td>Recommended Deformation Force (MPa)</td>
<td>55 (~27 tons / in²)</td>
</tr>
<tr>
<td>Breaking Strength (MPa)</td>
<td>1000 (~71 tons / in²)</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Work Output (Joule/g)</td>
<td>1</td>
</tr>
<tr>
<td>Energy Conversion Efficiency (%)</td>
<td>5</td>
</tr>
<tr>
<td>Maximum Deformation Ratio (%)</td>
<td>8</td>
</tr>
<tr>
<td>Recommended Deformation Ratio (%)</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Phase Related</strong></td>
<td></td>
</tr>
<tr>
<td>Phase Resistance (µΩ/cm)</td>
<td>76 82</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>28 75</td>
</tr>
<tr>
<td>Magnetic Susceptibility (µem/g)</td>
<td>2.5 5.0 6.2 9.5 12.5</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm°C)</td>
<td>0.08 0.18</td>
</tr>
</tbody>
</table>

### Poisson's Ratio
- Indicates how much a material narrows when pulled at each end (i.e. the cross-sectional shrinkage in a material under strain). For metal it is about 0.33 (the same as aluminum). Like Young's Modulus, the ratio varies widely and depends greatly on the alloy's composition, training and temperature.

### Electrical Properties
- Voltage, current, and resistance of a Muscle Wire follow the basic equation of electricity, Ohm's Law:
  \[ V = I \times R \]
- Voltage (in volts) equals current (in amperes) times resistance (in ohms)

So if you know the wire's resistance (which varies directly with its length) and the recommended current level to activate it, you can calculate the required voltage by using Ohm's Law. For example, a 10 cm MuscleWires.com

Figure 2.8 Flexinol Muscle Wire Properties
- This table shows values for various sizes of Flexinol Muscle Wires that have a transition temperature of 20°C.

http://www.robotstore.com/download/MWPBv4.00_FlexSpecs.pdf

A.9
Appendix B

Technical drawings
Appendix C

Maple code

A) WORKSPACE FORMULAS C.2
B) SINGULARITIES CALCULATION C.4
C) SINGULARITIES GRAPH C.8
D) WORKSPACE AND SINGULARITIES DATABASE: QUERY I C.13
E1) WORKSPACE AND SINGULARITIES DATABASE: QUERY I C.16
E2) WORKSPACE AND SINGULARITIES DATABASE: QUERY II C.18
E3) WORKSPACE AND SINGULARITIES DATABASE: QUERY III C.20
Appendix C

A) WORKSPACE FORMULAS

Denavit-Hartemberg parameters for the surgery arm

<table>
<thead>
<tr>
<th>Joint</th>
<th>( \alpha )</th>
<th>( \theta )</th>
<th>( d )</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>( \theta_1 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>( \theta_2 )</td>
<td>0</td>
<td>( a_2 )</td>
</tr>
<tr>
<td>3</td>
<td>-( \frac{\pi}{2} )</td>
<td>( \theta_3 )</td>
<td>0</td>
<td>( a_3 )</td>
</tr>
<tr>
<td>4</td>
<td>( \frac{\pi}{2} )</td>
<td>( \theta_4 )</td>
<td>( d_4 )</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>-( \frac{\pi}{2} )</td>
<td>( \theta_5 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>( \frac{\pi}{2} )</td>
<td>( \theta_6 )</td>
<td>( d_6 )</td>
<td>0</td>
</tr>
</tbody>
</table>

Determine the position and orientation of the tip of this robot arm as a function of the kinematic parameters. Also describe the translational and rotational velocity of the tip.

> restart;

Definition of the Denavit-Hartenberg matrices (Output: matrix 4X4)

\[
M(a, \alpha, d, \theta) \rightarrow \begin{bmatrix}
\cos(\theta) & -\sin(\theta) & 0 & a \\
\sin(\theta) \cos(\alpha) & \cos(\theta) \cos(\alpha) & -\sin(\alpha) & -\sin(\alpha) d \\
\sin(\theta) \sin(\alpha) & \cos(\theta) \sin(\alpha) & \cos(\alpha) & \cos(\alpha) d \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Calculation of the instrument link transformations (Output: 6 matrices 4X4)

alpha := vector([0, 0, -Pi/2, +Pi/2, -Pi/2, +Pi/2]):
d := vector([0$6]):

> theta := vector(6):
a[1]:=0: a[2]:=50: a[3]:=15: a[4]:=0: a[5]:=0: a[6]:=0:
d[1]:=0: d[2]:=0: d[3]:=0: d[4]:=36: d[5]:=0: d[6]:=+39.5:

> for i to 6 do
\[ A[i] := M( a[i], \alpha[i], d[i], \theta[i] ) \]
\textbf{od;}

Computation of the posture of the end effector \textit{(Output: matrix 4X4).}
The posture is computed for a specified set of DoF angle values.

The arm is disposed along a line with the following values of the DoF coordinates:
\[ \theta[5] := 0.0: \theta[6] := 0.0: \]
\[ > \theta[1] := 7.0: \theta[2] := 0.0: \theta[3] := 0.0: \]

\[ \text{Tip} := \text{evalm( `&*`( seq( A[i], i=1..6 ) ) )}; \]

The orientation of the tip is described be the following matrix. \textit{(Output: matrix 3X3)}

\[ \text{Tip} := \begin{bmatrix}
-0.7947380861 & -0.6069525308 & 0.49.00364653 \\
0.6069525308 & -0.7947380861 & 0.42.70412892 \\
0.0.0.1.75.5 \\
0.0.0.1. \\
\end{bmatrix} \]

Computation of the position of end effector; coordinates x, y, z \textit{(Output: vector 3X1)}

\[ \text{T} := \text{subvector( Tip , 1..3, 4 )}; \]

\[ T := [49.00364653, 42.70412892, 75.5] \]

The orientation of the tip is described be the following matrix. \textit{(Output: matrix 3X3)}

\[ \text{R} := \text{submatrix( Tip , 1..3, 1..3 )}; \]

\[ R := \begin{bmatrix}
-0.7947380861 & -0.6069525308 & 0.7947380861 \\
0.6069525308 & -0.7947380861 & 0.0.0.1. \\
0.0.0.1. \\
\end{bmatrix} \]
Appendix C

****************************
****************************
B) SINGULARITIES CALCULATION

Computation of the determinant of the velocity matrix

> restart;

with(linalg):

Warning, the protected names norm and trace have been redefined and unprotected

Definition of the Denavit-Hartenberg matrices (Output: matrix 4X4)

> M := (a,alpha,d,theta) -> matrix( 4, 4, [
  cos(theta), -sin(theta), 0, a,
  sin(theta)*cos(alpha), cos(theta)*cos(alpha), -sin(alpha), -sin(alpha)*d,
  sin(theta)*sin(alpha), cos(theta)*sin(alpha), cos(alpha),
  cos(alpha)*d,
  0, 0, 0, 1 ] );

> M(a,alpha,d,theta):

Calculation of the instrument link transformations (Output: 6 matrices 4X4)

alpha := vector([0,0,-Pi/2,+Pi/2,-Pi/2,+Pi/2]):
d := vector([0$6]):
theta := vector(6):

a[1]:=0: a[2]:=50: a[3]:=15: a[4]:=0:  a[5]:=0: a[6]:=0:
d[1]:=0: d[2]:=0:  d[3]:=0:  d[4]:=36: d[5]:=0: d[6]:=+39.5:  

for i to 6 do
  A[i] := M( a[i], alpha[i], d[i], theta[i] )
od:

Computation of the posture of the end effector  (Output: matrix 4X4).
The posture is computed for a specified set of DoF angle values.

The arm is disposed along a line with the following values of the DoF coordinates:
theta[1]:=0.0: theta[2]:=0.0: theta[3]:=1.57: theta[4]:=0.0: theta[5]:=0.0: theta[6]:=0.0:

> #theta[1]:=1.0: theta[2]:=0.8: theta[3]:=0.3:  
#theta[4]:=0.4: theta[5]:=0.7: theta[6]:=0.2:  

> Tip := evalm( `&*`( seq( A[i], i=1..6 ) ) );

C-4
Tip :=
[ ( ( ( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) cos( T3 ) cos( T4 )
( cos( T1 ) sin( T2 )sin( T1 ) cos( T2 ) ) sin( T4 ) ) cos( T5 )
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) sin( T3 ) sin( T5 ) ) cos( T6 )(

( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) cos( T3 ) sin( T4 )
( cos( T1 ) sin( T2 )sin( T1 ) cos( T2 ) ) cos( T4 ) ) sin( T6 ) , ( (
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) cos( T3 ) cos( T4 )
( cos( T1 ) sin( T2 )sin( T1 ) cos( T2 ) ) sin( T4 ) ) cos( T5 )
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) sin( T3 ) sin( T5 ) ) sin( T6 )(
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) cos( T3 ) sin( T4 )
( cos( T1 ) sin( T2 )sin( T1 ) cos( T2 ) ) cos( T4 ) ) cos( T6 ) , (
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) cos( T3 ) cos( T4 )

( cos( T1 ) sin( T2 )sin( T1 ) cos( T2 ) ) sin( T4 ) ) sin( T5 )
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) sin( T3 ) cos( T5 ) , 39.5 (
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) cos( T3 ) cos( T4 )
( cos( T1 ) sin( T2 )sin( T1 ) cos( T2 ) ) sin( T4 ) ) sin( T5 )
39.5 ( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) sin( T3 ) cos( T5 )

36 ( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) sin( T3 )15 cos( T1 ) cos( T2 )
15 sin( T1 ) sin( T2 )50 cos( T1 ) ]
[ ( ( ( sin( T1 ) cos( T2 )cos( T1 ) sin( T2 ) ) cos( T3 ) cos( T4 )
( cos( T1 ) cos( T2 )sin( T 1 ) sin( T2 ) ) sin( T4 ) ) cos( T5 )
( sin( T1 ) cos( T 2 )cos( T 1 ) sin( T2 ) ) sin( T3 ) sin( T5 ) ) cos( T6 )(
( sin( T1 ) cos( T2 )cos( T1 ) sin( T2 ) ) cos( T3 ) sin( T 4 )
( cos( T1 ) cos( T2 )sin( T 1 ) sin( T2 ) ) cos( T4 ) ) sin( T6 ) , ( (
( sin( T1 ) cos( T2 )cos( T1 ) sin( T2 ) ) cos( T3 ) cos( T4 )

( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) sin( T4 ) ) cos( T5 )
( sin( T1 ) cos( T2 )cos( T1 ) sin( T2 ) ) sin( T3 ) sin( T5 ) ) sin( T6 )(
( sin( T1 ) cos( T2 )cos( T1 ) sin( T2 ) ) cos( T3 ) sin( T4 )

( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) cos( T 4 ) ) cos( T6 ) , (
( sin( T1 ) cos( T2 )cos( T1 ) sin( T2 ) ) cos( T3 ) cos( T4 )
( cos( T1 ) cos( T2 )sin( T1 ) sin( T2 ) ) sin( T4 ) ) sin( T5 )
( sin( T1 ) cos( T2 )cos( T1 ) sin( T2 ) ) sin( T3 ) cos( T5 ) , 39.5 (
( sin( T1 ) cos( T 2 )cos( T 1 ) sin( T2 ) ) cos ( T3 ) cos ( T4 )
( cos( T 1 ) cos( T 2 )sin( T1 ) sin( T 2 ) ) sin( T4 ) ) sin( T 5 )
39.5 ( sin( T 1 ) cos ( T2 )cos( T 1 ) sin( T 2 ) ) sin( T3 ) cos( T 5 )
36 ( sin( T1 ) cos( T 2 )cos( T 1 ) sin( T2 ) ) sin( T 3 )15 sin( T1 ) cos ( T2 )

C-5


Appendix C

C-6

\[ R := \text{submatrix}( \text{Tip}, 1..3, 1..3 ); \]

\[ T := \text{subvector}( \text{Tip}, 1..3, 4 ); \]

Computation of the position of end effector; coordinates x, y, z (Output: vector 3X1)

\[
T := \left[ \begin{array}{c}
39.5 \left( (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \cos(\theta_3) \cos(\theta_4) \\
+ (-\cos(\theta_1) \sin(\theta_2) - \sin(\theta_1) \cos(\theta_2)) \sin(\theta_3) \\
+ 39.5 \left( (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \sin(\theta_3) \cos(\theta_4) \\
+ 36 \left( (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \sin(\theta_3) + 15 \cos(\theta_1) \cos(\theta_2) \\
- 15 \sin(\theta_1) \sin(\theta_2) + 50 \cos(\theta_1), 39.5 \left( (\sin(\theta_1) \cos(\theta_2) + \cos(\theta_1) \sin(\theta_2)) \cos(\theta_3) \cos(\theta_4) \\
+ (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \sin(\theta_3) \sin(\theta_4) \\
+ 39.5 \left( (\sin(\theta_1) \cos(\theta_2) + \cos(\theta_1) \sin(\theta_2)) \sin(\theta_3) \cos(\theta_4) \\
+ 36 \left( (\sin(\theta_1) \cos(\theta_2) + \cos(\theta_1) \sin(\theta_2)) \sin(\theta_3) + 15 \sin(\theta_1) \cos(\theta_2) \\
+ 15 \cos(\theta_1) \sin(\theta_2) + 50 \sin(\theta_1), -39.5 \sin(\theta_1) \cos(\theta_2) \sin(\theta_3) + 39.5 \cos(\theta_1) \cos(\theta_2) + 36 \cos(\theta_3) \right) \\
\right) \right) \right]
\]

The orientation of the tip is described by the following matrix.(Output: matrix 3X3)

\[
R := \left[ \begin{array}{c}
( (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \cos(\theta_3) \cos(\theta_4) \\
+ (-\cos(\theta_1) \sin(\theta_2) - \sin(\theta_1) \cos(\theta_2)) \sin(\theta_3) \cos(\theta_4) \\
- (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \sin(\theta_3) \sin(\theta_4) + ( \\
- (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \cos(\theta_3) \cos(\theta_4) \\
+ (-\cos(\theta_1) \sin(\theta_2) - \sin(\theta_1) \cos(\theta_2)) \sin(\theta_3) \sin(\theta_4), - ( \\
(\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \cos(\theta_3) \cos(\theta_4) \\
+ (-\cos(\theta_1) \sin(\theta_2) - \sin(\theta_1) \cos(\theta_2)) \sin(\theta_3) \cos(\theta_4) \\
- (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \sin(\theta_3) \sin(\theta_4) + ( \\
- (\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \cos(\theta_3) \cos(\theta_4) \\
+ (-\cos(\theta_1) \sin(\theta_2) - \sin(\theta_1) \cos(\theta_2)) \sin(\theta_3) \sin(\theta_4), ( \\
(\cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2)) \cos(\theta_3) \cos(\theta_4) \\
\right) \right) \right]
\]

C-6
The Velox matrix is computed using the screw theory (Output: matrix 6X6)
The posture is computed for a specified set of DoF angle values.
The determinant of the Velox matrix is used to verify if the given configuration of the arm is singular.

> MMM:=A[1]:
S_temp1:=evalm(MMM&*[0,0,1,0]):
S_temp2:=evalm(MMM&*[0,0,0,1]):
S_temp3:=crossprod( [S_temp2[1],S_temp2[2],S_temp2[3]],
                  [S_temp1[1],S_temp1[2],S_temp1[3]]):
S1:=[S_temp1[1],S_temp1[2],S_temp1[3],S_temp3[1],S_temp3[2],S_temp3[3]]:

S_temp1:=evalm(MMM&*[0,0,1,0]):
S_temp2:=evalm(MMM&*[0,0,0,1]):
S_temp3:=crossprod( [S_temp2[1],S_temp2[2],S_temp2[3]],
                  [S_temp1[1],S_temp1[2],S_temp1[3]]):
S2:=[S_temp1[1],S_temp1[2],S_temp1[3],S_temp3[1],S_temp3[2],S_temp3[3]]:

S_temp1:=evalm(MMM&*[0,0,1,0]):
S_temp2:=evalm(MMM&*[0,0,0,1]):
S_temp3:=crossprod( [S_temp2[1],S_temp2[2],S_temp2[3]],
                  [S_temp1[1],S_temp1[2],S_temp1[3]]):
S3:=[S_temp1[1],S_temp1[2],S_temp1[3],S_temp3[1],S_temp3[2],S_temp3[3]]:

S_temp1:=evalm(MMM&*[0,0,1,0]):
S_temp2:=evalm(MMM&*[0,0,0,1]):
S_temp3:=crossprod( [S_temp2[1],S_temp2[2],S_temp2[3]],
                  [S_temp1[1],S_temp1[2],S_temp1[3]]):
\[ S_4 := [S_{\text{temp1}[1]}, S_{\text{temp1}[2]}, S_{\text{temp1}[3]}, S_{\text{temp3}[1]}, S_{\text{temp3}[2]}, S_{\text{temp3}[3]}] ; \]

\[ S_{\text{temp1}} := \text{evalm}(\text{MMM} \&* [0, 0, 1, 0]) ; \]
\[ S_{\text{temp2}} := \text{evalm}(\text{MMM} \&* [0, 0, 0, 1]) ; \]
\[ S_{\text{temp3}} := \text{crossprod}( [S_{\text{temp2}[1]}, S_{\text{temp2}[2]}, S_{\text{temp2}[3]}] , [S_{\text{temp1}[1]}, S_{\text{temp1}[2]}, S_{\text{temp1}[3]}] ) ; \]
\[ S_5 := [S_{\text{temp1}[1]}, S_{\text{temp1}[2]}, S_{\text{temp1}[3]}, S_{\text{temp3}[1]}, S_{\text{temp3}[2]}, S_{\text{temp3}[3]}] ; \]

\[ S_{\text{temp1}} := \text{evalm}(\text{MMM} \&* [0, 0, 1, 0]) ; \]
\[ S_{\text{temp2}} := \text{evalm}(\text{MMM} \&* [0, 0, 0, 1]) ; \]
\[ S_{\text{temp3}} := \text{crossprod}( [S_{\text{temp2}[1]}, S_{\text{temp2}[2]}, S_{\text{temp2}[3]}] , [S_{\text{temp1}[1]}, S_{\text{temp1}[2]}, S_{\text{temp1}[3]}] ) ; \]
\[ S_6 := [S_{\text{temp1}[1]}, S_{\text{temp1}[2]}, S_{\text{temp1}[3]}, S_{\text{temp3}[1]}, S_{\text{temp3}[2]}, S_{\text{temp3}[3]}] ; \]

\[ J := \text{blockmatrix}(1, 6, [S_1, S_2, S_3, S_4, S_5, S_6]) ; \]

\[ \text{deterJ} := \text{det}(J) ; \]
\[ e_1 := \text{simplify}(\text{deterJ}) ; \]
\[ e_1 := -5400 \sin(\theta_2) \sin(\theta_3) (5 + 12 \sin(\theta_3)) \]

\[ \text{solve}(e_1) ; \]
\[ \{ \theta_1 = 0, \theta_2 = 0, \theta_3 = \theta_5 \}, \{ \theta_1 = 0, \theta_2 = 0, \theta_3 = \theta_5 \}, \{ \theta_1 = 0, \theta_3 = \theta_5, \theta_2 = \theta_5 \}, \{ \theta_1 = 0, \theta_2 = \theta_5, \theta_3 = \theta_5 \}, \{ \theta_2 = -\arcsin\left(\frac{5}{12}\right), \theta_2, \theta_3 = \theta_5 \} \]

C) SINGULARITIES GRAPH

Graph of the singularities workspace

\[ t_1 := 0 ; t_4 := 0 ; \]
\[ t_2 := t_2 ; t_3 := t_3 ; t_5 := 0 ; \]
\[ \text{restart} ; \]
\[ \text{plot3d(} [ \]
\[ 39.5*( \cos(0)*\cos(t_2)-\sin(0)*\sin(t_2) )*\cos(t_3)*\cos(0)+(-\cos(0)*\sin(t_2)-\sin(0)*\cos(t_2))*\sin(0)+39.5*(\cos(0)*\cos(t_2)-\sin(0)*\sin(t_2))*\sin(t_3)+36*(\cos(0)*\cos(t_2)-\sin(0)*\sin(t_2))*\sin(t_3)+15*(\cos(0)*\cos(t_2)-\sin(0)*\sin(t_2))*\sin(t_3)+50*\cos(0) , \]
\[ 39.5*( \sin(0)*\cos(t_2)+\cos(0)*\sin(t_2) )*\cos(t_3)*\cos(0)+(-\sin(0)*\sin(t_2)+\cos(0)*\cos(t_2))*\sin(0)+39.5*(\sin(0)*\cos(t_2)+\cos(0)*\sin(t_2))*\sin(t_3)+36*(\sin(0)*\cos(t_2)+\cos(0)*\sin(t_2))*\sin(t_3)+15*(\sin(0)*\cos(t_2)+\cos(0)*\sin(t_2))*\sin(t_3)+50*\sin(0) , \]
\[ ] , t_2 = -\pi/2 .. \pi/2 , t_3 = -\pi/2 .. \pi/2 , \]

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restart;
plot3d( [ 
39.5*((cos(0)*cos(t2) - sin(0)*sin(t2))*cos(0)*cos(0) + (-cos(0)*sin(t2) - 
  sin(0)*cos(t2))*sin(0))*sin(t5) + 39.5*(cos(0)*cos(t2) - 
  sin(0)*sin(t2))*sin(0)*cos(t5) + 36*(cos(0)*cos(t2) - 
  sin(0)*sin(t2))*sin(0) + 15*cos(0) + 50*cos(0), 
39.5*((sin(0)*cos(t2) + cos(0)*sin(t2))*cos(0)*cos(0) + (cos(0)*cos(t2) - 
  sin(0)*sin(t2))*sin(0))*sin(t5) + 39.5*(sin(0)*cos(t2) + cos(0)*sin(t2)) * 
  sin(0)*cos(t5) + 36*(sin(0)*cos(t2) + cos(0)*sin(t2))*sin(0) + 15*sin(0)*cos 
  (t2) + 15*sin(0)*cos(t2) + 50*sin(0), - 
39.5*sin(0)*cos(t5) + 39.5*cos(0)*cos(t5) + 36*cos(0) 
], t2=-Pi/2..Pi/2, t5=-Pi/2..Pi/2, 
  style=patch, axes=frame, orientation=[50,75] );
Appendix C

t2:=0: t3:=t3: t5:=t5:

> restart;
plot3d( [ 39.5*(cos(0)*cos(0)-sin(0)*sin(0))*cos(t3)*cos(0)+(-cos(0)*sin(0)-
sin(0)*cos(0))*sin(t5)+39.5*(cos(0)*cos(0)-
  sin(0)*sin(0))*sin(t3)*cos(t5)+36*(cos(0)*cos(0)-
  sin(0)*sin(0))*sin(t3)+15*cos(0)*cos(0)-
  15*sin(0)*sin(0)+50*cos(0),
  39.5*(sin(0)*cos(0)+cos(0)*sin(0))*cos(t3)*cos(0)+(cos(0)*cos(0)-
  sin(0)*sin(0))*sin(t5)+39.5*(sin(0)*cos(0)+cos(0)*sin(0))*sin(t3)+15*sin(0)*cos(0)-
  15*cos(0)*sin(0)+50*sin(0),
  -39.5*sin(t3)*cos(0)*sin(t5)+39.5*cos(t3)*cos(t5)+36*cos(t3) ],
  t3=-Pi/2..Pi/2, t5=-Pi/2..Pi/2,
  style=patch, axes=frame, orientation=[50,75] );

> 

> t1:=0: t4:=0:

> t2:=t2: t3:=-arcsin(5/12): t5:=t5:

> restart;
plot3d( [ 39.5*(cos(0)*cos(t2)-sin(0)*sin(t2))*cos(-arcsin(5/12))*cos(0)+(-
  cos(0)*sin(t2)-sin(0)*cos(t2))*sin(0))*sin(t5)+39.5*(cos(0)*cos(t2)-
  sin(0)*sin(t2))*sin(-arcsin(5/12))*cos(t5)+36*(cos(0)*cos(t2)-
  sin(0)*sin(t2))*sin(-arcsin(5/12)+15*cos(0)*cos(t2)-
  15*sin(0)*sin(t2)+50*cos(0),
  39.5*(sin(0)*cos(t2)+cos(0)*sin(t2))*cos(-
  arcsin(5/12))*cos(0)+(-
  sin(0)*sin(t2))*sin(t5)+39.5*(sin(0)*cos(t2)+cos(0)*sin(t2))*
  sin(-arcsin(5/12))*cos(t5)+36*(sin(0)*cos(t2)+cos(0)*sin(t2))*sin(-
  arcsin(5/12)+15*cos(0)*sin(t2)+15*cos(0)*sin(t2)+50*sin(0),
  -39.5*sin(-arcsin(5/12))*cos(0)*sin(t5)+39.5*cos(-
  arcsin(5/12))*cos(t5)+36*cos(-arcsin(5/12)) ],
  t2=-Pi/2..Pi/2, t5=-Pi/2..Pi/2, style=patch, axes=frame,
  orientation=[50,75] );

>
> t1:=0: t4:=0: t2:=t2: t3:=-Pi+arcsin(5/12): t5:=t5:
> restart:
plot3d( [39.5*((cos(0)*cos(t2)-sin(0)*sin(t2))*cos(-Pi+arcsin(5/12))*cos(0)+(-
cos(0)*sin(t2)-sin(0)*cos(t2))*sin(0))*sin(t5)+39.5*(cos(0)*cos(t2)-
sin(0)*sin(t2))*sin(-Pi+arcsin(5/12))*cos(t5)+36*(cos(0)*cos(t2)-
sin(0)*sin(t2))*sin(-Pi+arcsin(5/12))+15*cos(0)*cos(t2)-
15*sin(0)*sin(t2)+50*cos(0),
39.5*((sin(0)*cos(t2)+cos(0)*sin(t2))*cos(-
Pi+arcsin(5/12))*cos(0)+(cos(0)*cos(t2)-
sin(0)*sin(t2))*sin(t5)+39.5*(sin(0)*cos(t2)+cos(0)*sin(t2))*sin(-
Pi+arcsin(5/12))*cos(0)+50*sin(0),
39.5*sin(-Pi+arcsin(5/12))*cos(0)*sin(t5)+39.5*cos(-Pi+arcsin(5/12))*cos(t5)+36*cos(-Pi+arcsin(5/12)))
], t2=-Pi/2..Pi/2, t5=-Pi/2..Pi/2, style=patch, axes=frame, orientation=[50,75] );
15*sin(0)*sin(t2)+50*cos(0),
39.5* ( (sin(0)*cos(t2)+cos(0)*sin(t2)) *cos(t3) *cos(0) + (cos(0)*cos(t2) -
   sin(t2)) *sin(0) ) *sin(0) + 39.5* ( (sin(0)*cos(t2)+cos(0)*sin(t2)) *sin(t2) *cos(t3) + 36* (sin(0) *cos(t2)+cos(0)*sin(t2)) *cos(t3) *cos(0) + 50* sin(0) ),
39.5* ( sin(t3) *cos(0) *sin(0) + 39.5* cos(t3) *cos(0) + 36* cos(t3) ) :

\[ c_2 := [39.5*(cos(0)*cos(t2)-sin(0)*sin(t2))*cos(0)*cos(0)+(-
   cos(0)*sin(t2)-sin(0)*cos(t2))*sin(0)]*sin(t3)+39.5*(cos(0)*cos(t2)-
   sin(t2)) *sin(0) *cos(t3) + 36* (cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(0) *cos(t3) + 15*cos(0) *cos(t2) + 50* sin(0),
39.5* ( (sin(0)*cos(t2)+cos(0)*sin(t2)) *cos(t3) *cos(0) + (cos(0)*cos(t2) -
   sin(0) *sin(t2) ) *sin(0) *cos(t3) + 39.5* (sin(0) *cos(t2)+cos(0)*sin(t2)) *sin(t3) + 15*sin(0) *cos(t2) + 50* sin(0),
   - 39.5* (sin(0) *cos(t3) *sin(t3) ) + 39.5* cos(t3) *cos(0) + 36* cos(t3) ] :

\[ c_3 := [39.5*(cos(0)*cos(t2)-sin(0)*sin(t2))*cos(0)*cos(0)+(-
   cos(0)*sin(t2)-sin(0)*cos(t2))*sin(0)]*sin(t3)+39.5*(cos(0)*cos(t2)-
   sin(t2)) *sin(0) *cos(t3) + 36* (cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(0) *cos(t3) + 15*cos(0) *cos(t2) + 50* sin(0),
39.5* ( (sin(0)*cos(t2)+cos(0)*sin(t2)) *cos(t3) *cos(0) + (cos(0)*cos(t2) -
   sin(0) *sin(t2) ) *sin(0) *cos(t3) + 39.5* (sin(0) *cos(t2)+cos(0)*sin(t2)) *sin(t3) + 15*sin(0) *cos(t2) + 50* sin(0),
   - 39.5* (sin(t3) *cos(0) *sin(t2) ) + 39.5* cos(t3) *cos(0) + 36* cos(t3) ] :

\[ c_4 := [39.5*(cos(0)*cos(t2)-sin(0)*sin(t2))*cos(-
   arcsin(5/12)) *cos(0) + (-cos(0) *sin(t2) -
   sin(0) *cos(t2) ) *sin(t3) + 39.5*(cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(t3) + 36* (cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(t3) + 15*cos(0) *cos(t2) -
   15* sin(0) *sin(t2) + 50* sin(0),
39.5* ( (sin(0)*cos(t2)+cos(0)*sin(t2)) *cos(-
   arcsin(5/12)) *cos(0) + (cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(t3) + 39.5* (sin(0) *cos(t2)+cos(0)*sin(t2)) *sin(-
   arcsin(5/12)) *cos(t3) + 36* (sin(0) *cos(t2) + cos(0) *sin(t2)) *sin(-
   arcsin(5/12)) + 15*sin(0) *cos(t2) + 50* sin(0),
   - 39.5* (sin(-arcsin(5/12)) *cos(0) *sin(t3) + 39.5* cos(-
   arcsin(5/12)) *cos(t3) + 36* (-arcsin(5/12)) ] :

\[ c_5 := [39.5*(cos(0)*cos(t2)-sin(0)*sin(t2))*cos(-
   Pi+arcsin(5/12)) *cos(0) + (-cos(0) *sin(t2) -
   sin(0) *cos(t2) ) *sin(t3) + 39.5*(cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(-Pi+arcsin(5/12)) *cos(t3) + 36* (cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(-Pi+arcsin(5/12)) + 15*cos(0) *cos(t2) -
   15* sin(0) *sin(t2) + 50* sin(0),
39.5* ( (sin(0)*cos(t2)+cos(0)*sin(t2)) *cos(-
   Pi+arcsin(5/12)) *cos(0) + (cos(0) *cos(t2) -
   sin(0) *sin(t2) ) *sin(t3) + 39.5* (sin(0) *cos(t2)+cos(0)*sin(t2)) *sin(-
   Pi+arcsin(5/12)) *cos(t3) + 36* (sin(0) *cos(t2) + cos(0) *sin(t2)) *sin(-
   Pi+arcsin(5/12)) + 15*sin(0) *cos(t2) + 50* sin(0),
   - 39.5* (sin(-Pi+arcsin(5/12)) *cos(0) *sin(t3) + 39.5* cos(-
   Pi+arcsin(5/12)) *cos(t3) + 36* (-Pi+arcsin(5/12)) ] :

plot3d([c1, c2, c3, c4, c5], t2= Pi/2.. Pi/2, t3= Pi/2.. Pi/2,
   grid=[25,15], style=patch);
D) WORKSPACE AND SINGULARITIES DATABASE: CREATION

Graph of the singularities workspace

Calculation of the robot workspace. (Output: file "xyz.txt" containing n lines each of 19 values)
Each arm DoF can assume a range of angular positions. The span of each DoF is limited by the
geometry of the arm;
for example theta[5] can assume values from -Pi/2 to +Pi/2

The program assignes to each (of the six) arm DoF a discrete set of possible angular positions.

For each set of six DoF values the following 19 values are computed and saved in the xyz file:
- x,y,z position of the end effector (vector 3X1)
- angular position of the end effector (matrix 3X3)
- determinant of the Jacobian (scalar)

The variable step1 is the sampling step; "step1:=31:" means that the step from a theta to the following
one is 31 degrees

Orientation of the end effector parallel to base frame matrix 3X3:
1,0,0 0,1,0 0,0,1

Orientation of the end effector (Z coordinate) perpendicular (+90°) to base frame matrix 3X3:
1,0,0 0,0,1

End effector coordinates x,y,z

> Z:=(t1,t2,t3,t4,t5,t6)->vector([

39.5*((cos(t1)*cos(t2)-sin(t1)*sin(t2))*cos(t3)*cos(t4)+(-cos(t1)*sin(t2)
- sin(t1)*cos(t2))*sin(t4))*sin(t5)+39.5*(cos(t1)*cos(t2)-sin(t1)*sin(t2))*sin(t3)*cos(t5)+36*(cos(t1)*cos(t2)
- sin(t1)*cos(t2))*sin(t3)+15*cos(t1)*cos(t2)-
15*sin(t1)*sin(t2)+50*cos(t1),

39.5*((sin(t1)*cos(t2)+cos(t1)*sin(t2))*cos(t3)*cos(t4)+(-cos(t1)*sin(t2)
- sin(t1)*cos(t2))*sin(t4))*sin(t5)+39.5*(sin(t1)*cos(t2)+cos(t1)*sin(t2))*sin(t3)*cos(t5)+36*(sin(t1)*cos(t2)
- sin(t1)*cos(t2))*sin(t3)+15*sin(t1)*cos(t2)-
15*sin(t1)*sin(t2)+50*sin(t1),

-39.5*sin(t3)*cos(t4)*sin(t5)+39.5*cos(t3)*cos(t5)+36*cos(t3)

C-13
End effector orientation (matrix 3X3)

\[
F:=(t_1,t_2,t_3,t_4,t_5,t_6)\rightarrow \text{linalg}[\text{matrix}](3,3, \\
[ (\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\cos(t_1)\sin(t_2)-\sin(t_1)\cos(t_2))\sin(t_4)\cos(t_5)\cos(t_6)+(-\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\sin(t_3)\sin(t_5)\cos(t_6), \\
-((\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\cos(t_1)\sin(t_2)-\sin(t_1)\cos(t_2))\sin(t_4)\cos(t_5)\sin(t_6)+(-\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\sin(t_3)\sin(t_5)\sin(t_6), \\
((\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\cos(t_1)\sin(t_2)-\sin(t_1)\cos(t_2))\sin(t_4)\sin(t_5)\sin(t_6), \\
-((\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\cos(t_1)\sin(t_2)-\sin(t_1)\cos(t_2))\sin(t_4)\cos(t_5)\cos(t_6), \\
((\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\cos(t_1)\sin(t_2)-\sin(t_1)\cos(t_2))\sin(t_4)\sin(t_5)\sin(t_6), \\
-((\cos(t_1)\cos(t_2)-\sin(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\cos(t_1)\sin(t_2)-\sin(t_1)\cos(t_2))\sin(t_4)\cos(t_5)\cos(t_6), \\
((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\sin(t_5)\sin(t_6), \\
-((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\cos(t_5)\cos(t_6), \\
((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\sin(t_5)\sin(t_6), \\
-((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\cos(t_5)\cos(t_6), \\
((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\sin(t_5)\sin(t_6), \\
-((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\cos(t_5)\cos(t_6), \\
((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\sin(t_5)\sin(t_6), \\
-((\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\cos(t_3)\cos(t_4)+(-\sin(t_1)\cos(t_2)+\cos(t_1)\sin(t_2))\sin(t_4)\cos(t_5)\cos(t_6))]:
\]

Det of Velocity Matrix (scalar)

\[
DJCBN:=(t_2,t_3,t_5)\rightarrow \sin(t_2)\sin(t_3)\sin(t_5)\sin(5+12\sin(t_3)):
\]

unassign('xyz'); unassign('count');

file:= fopen ("xyz.txt", WRITE);

step1:=1:
> for n from -10 by step 1 to 9 do
    for o from -5 by step 1 to 5 do
        print(n, o);
        for p from 0 by step 1 to 10 do
            for q from -10 by step 1 to 9 do
                for r from -5 by step 1 to 5 do
                    for s from -10 by step 1 to 9 do
                        theta[1] := 3.141592 * (n/10):
                        pos := Z(theta[1], theta[2], theta[3], theta[4], theta[5], theta[6]):
                        ori := F(theta[1], theta[2], theta[3], theta[4], theta[5], theta[6]):
                        djac := DJCBN(theta[2], theta[3], theta[5]):
                        evalm(pos):
                        evalm(ori):
                        evalm(jacb):
                        if (xyz<>NULL) then
                            xyz:=xyz:
                            fprintf(file, "%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f
\n",
                            theta[1]*57.29747, theta[2]*57.29747, theta[3]*57.29747,
                            theta[4]*57.29747, theta[5]*57.29747, theta[6]*57.29747,
                            pos[1], pos[2], pos[3],
                            djac,
                            evalm(ori[1,1]), evalm(ori[1,2]), evalm(ori[1,3]),
                            evalm(ori[2,1]), evalm(ori[2,2]), evalm(ori[2,3]),
                            evalm(ori[3,1]), evalm(ori[3,2]), evalm(ori[3,3])
                        );
                        else
                            xyz:=erfd:
                        end if;
                    od: od: od: od: od: od:
        fclose(file):
    Graph of the robot workspace; # function disabled (Output: 3D graph of point cloud).

> #pointplot3d({pippo}, axes=NONE):
> #print(pippo):
> #with(plots):
> #pointplot3d({pippo }, axes=NONE, thickness=3);
>
E1) WORKSPACE AND SINGULARITIES DATABASE: QUERY I

Four graphs of workspaces

The program reads the file
   00-XYZsource.txt (this file was previously cold xyz.txt)
and write the files:
   01-FullWorksp.txt, 02-ParaXWorksp.txt, 03-ParaXSingul.txt, 04-ParaXNoSing.txt

00-XYZsource.txt is the database of the mini-arm workspace/singularities created by program D
01-FullWorksp.txt contains the coordinates XYZ of all the points of the workspace
02-ParaXWorksp.txt contains the coordinates XYZ of the points of the workspace satisfying the condition:
   End effector Z // to base X0
03-ParaXSingul.txt contains the coordinates XYZ of the points of the workspace satisfying the conditions:
   End effector Z // to base X0
   Singular configuration
04-ParaXNoSing.txt contains the coordinates XYZ of the points of the workspace satisfying the conditions:
   End effector Z // to base X0
   Non singular configuration

> unassign('xyzall'); unassign('xyzsel');

input1:=NULL;
output1:=NULL;
output2:=NULL;
output3:=NULL;
output4:=NULL;

input1:= fopen ("00-XYZsource.txt", READ);
output1:= fopen ("01-FullWorksp.txt", WRITE);
output2:= fopen ("02-ParaXWorksp.txt", WRITE);
output3:= fopen ("03-ParaXSingul.txt", WRITE);
output4:= fopen ("04-ParaXNoSing.txt", WRITE);

cont:=0;

while (not feof(input1))
do:

   rli:=fscanf(input1, "%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f\n"):

   cont:=cont+1;

   if (rli[9]>0) then

      t1:=rli[1]; t2:=rli[2]; t3:=rli[3];
      t4:=rli[4]; t5:=rli[5]; t6:=rli[6];
x:=rli[7]; y:=rli[8]; z:=rli[9];
djac:=rli[10];
ori[1,1]:=rli[11]; ori[1,2]:=rli[12]; ori[1,3]:=rli[13];
ori[2,1]:=rli[14]; ori[2,2]:=rli[15]; ori[2,3]:=rli[16];
ori[3,1]:=rli[17]; ori[3,2]:=rli[18]; ori[3,3]:=rli[19];

#Para1:=( abs(abs(ori[1,1])-
0)+abs(abs(ori[1,2])+1)+abs(abs(ori[1,3])-
0)+abs(abs(ori[2,1])+1)+abs(abs(ori[2,2])-
0)+abs(abs(ori[2,3])-0)+
# abs(abs(ori[3,1])-0)+abs(abs(ori[3,2])-0)+
# abs(abs(ori[3,3])+1))/9;

ParaX:=( abs(abs(ori[1,3])-1)+abs(abs(ori[2,3])-0)+abs(abs(ori[3,3])-
0))/3;
ParaY:=( abs(abs(ori[1,3])-0)+abs(abs(ori[2,3])-1)+abs(abs(ori[3,3])-
0))/3;
ParaZ:=( abs(abs(ori[1,3])-0)+abs(abs(ori[2,3])-0)+abs(abs(ori[3,3])-
1))/3;

#if  ((cont/15)-trunc(cont/15))=0 then
if  ((cont/4)-trunc(cont/4))=0 then
  fprintf(output1,"%f %f %f\n", x, y, z):
end if:

if  (abs(ParaX)<=0.1) then
  fprintf(output2,"%f %f %f\n", x, y, z):
end if:

if  (abs(djac)<=0.0) and (abs(ParaX)<=0.1) then
  fprintf(output3,"%f %f %f\n", x, y, z):
end if:

if  (abs(djac)>0.0) and (abs(ParaX)<=0.1) then
  fprintf(output4,"%f %f %f\n", x, y, z):
end if:

end if:
end do:

fclose(input1):
fclose(output1):
fclose(output2):
fclose(output3):
fclose(output4):
E2) WORKSPACE AND SINGULARITIES DATABASE: QUERY II

Four graphs of workspaces

The program reads the file 00-XYZsource.txt (this file was previously cold xyz.txt) and write the files 05-ParaYWorksp.txt, 06-ParaYSingul.txt, 07-ParaYNoSing.txt

00-XYZsource.txt is the database of the mini-arm workspace/singularities created by program D
05-ParaYWorksp.txt contains the coordinates XYZ of the points of the workspace satisfying the condition:

End effector Z // to base Y0

06-ParaYSingul.txt contains the coordinates XYZ of the points of the workspace satisfying the conditions:

End effector Z // to base Y0
Singular configuration

07-ParaYNoSing.txt contains the coordinates XYZ of the points of the workspace satisfying the conditions:

End effector Z // to base Y0
Non singular configuration

> unassign('xyzall'); unassign('xyzsel');

input1:=NULL;
output1:=NULL;
output2:=NULL;
output3:=NULL;

input1:= fopen ("00-XYZsource.txt", READ);
output2:= fopen ("05-ParaYWorksp.txt", WRITE);
output3:= fopen ("06-ParaYSingul.txt", WRITE);
output4:= fopen ("07-ParaYNoSing.txt", WRITE);

cont:=0;

while (not feof(input1))
do:

ra:=fscanf(input1, "%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f
\n");

cont:=cont+1;

if (ra[9]>0) then

t1:=ra[1]; t2:=ra[2]; t3:=ra[3];
t4:=ra[4]; t5:=ra[5]; t6:=ra[6];
x:=ra[7]; y:=ra[8]; z:=ra[9];
djac:=rli[10]:
ori[1,1]:=rli[11]; ori[1,2]:=rli[12]; ori[1,3]:=rli[13];
ori[2,1]:=rli[14]; ori[2,2]:=rli[15]; ori[2,3]:=rli[16];
or[3,1]:=rli[17]; ori[3,2]:=rli[18]; ori[3,3]:=rli[19];

#Para1:=(abs(abs(ori[1,1])-0)+abs(abs(ori[1,2])+1)+abs(abs(ori[1,3])-0)+
# abs(abs(ori[2,1])+1)+abs(abs(ori[2,2])-0)+abs(abs(ori[2,3])-0)+
# abs(abs(ori[3,1])-0)+abs(abs(ori[3,2])-0)+abs(abs(ori[3,3])+1))/9;

ParaX:=(abs(abs(ori[1,3])-1)+abs(abs(ori[2,3])-0)+abs(abs(ori[3,3])-0))/3;
ParaY:=(abs(abs(ori[1,3])-0)+abs(abs(ori[2,3])-1)+abs(abs(ori[3,3])-0))/3;
ParaZ:=(abs(abs(ori[1,3])-0)+abs(abs(ori[2,3])-0)+abs(abs(ori[3,3])-1))/3;

if (abs(ParaY)<=0.1) then
    fprintf(output2, "%f %f %f\n", x, y, z):
end if:

if (abs(djac)<=0.0) and (abs(ParaY)<=0.1) then
    fprintf(output3, "%f %f %f\n", x, y, z):
end if:

if (abs(djac)>0.0) and (abs(ParaY)<=0.1) then
    fprintf(output4, "%f %f %f\n", x, y, z):
end if:

end if:
end do:

fclose(input1):
fclose(output1):
fclose(output2):
fclose(output3):
fclose(output4):
E3) WORKSPACE AND SINGULARITIES DATABASE: QUERY III

Four graphs of workspaces

The program reads the file
00-XYZsource.txt (this file was previously cold xyz.txt)
and write the files
08-ParaZWorksp.txt, 09-ParaZSingul.txt, 10-ParaZNoSing.txt

00-XYZsource.txt is the database of the mini-arm workspace/singularities created by program D
08-ParaZWorksp.txt contains the coordinates XYZ of the points of the workspace satisfying the condition:
   End effector Z // to base Z0
09-ParaZSingul.txt contains the coordinates XYZ of the points of the workspace satisfying the conditions:
   End effector Z // to base Z0
   Singular configuration
10-ParaZNoSing.txt contains the coordinates XYZ of the points of the workspace satisfying the conditions:
   End effector Z // to base Z0
   Non singular configuration

> unassign('xyzall'); unassign('xyzsel');

input1:=NULL;
output1:=NULL;
output2:=NULL;
output3:=NULL;

input1:= fopen ("00-XYZsource.txt", READ);
output2:= fopen ("08-ParaZWorksp.txt", WRITE);
output3:= fopen ("09-ParaZSingul.txt", WRITE);
output4:= fopen ("10-ParaZNoSing.txt", WRITE);

cont:=0;
while (not feof(input1))
do:
   rli:=fscanf(input1, "%f %f %f %f %f %f %f %f %f %f %f %f %f %f
%f %f %f\n");
   cont:=cont+1;
   #if (rli[9]>0) then
      t1:=rli[1]; t2:=rli[2]; t3:=rli[3];
t4:=rli[4]; t5:=rli[5]; t6:=rli[6];
x:=rli[7]; y:=rli[8]; z:=rli[9];
   endif

djac:=rli[10];
ori[1,1]:=rli[11]; ori[1,2]:=rli[12]; ori[1,3]:=rli[13];
or[2,1]:=rli[14]; ori[2,2]:=rli[15]; ori[2,3]:=rli[16];
or[3,1]:=rli[17]; ori[3,2]:=rli[18]; ori[3,3]:=rli[19];

#Para1:=((- abs(abs(ori[1,1]) - 0)+abs(abs(ori[1,2]) + 1)+abs(abs(ori[1,3]) - 0)+
# abs(abs(ori[2,1]) + 1)+abs(abs(ori[2,2]) - 0)+abs(abs(ori[2,3]) - 0)+
# abs(abs(ori[3,1]) - 0)+abs(abs(ori[3,2]) - 0)+abs(abs(ori[3,3]) + 1))/9);

ParaX:=( abs(abs(ori[1,3]) - 1)+abs(abs(ori[2,3]) - 0)+abs(abs(ori[3,3]) - 0))/3;
ParaY:=( abs(abs(ori[1,3]) - 0)+abs(abs(ori[2,3]) - 1)+abs(abs(ori[3,3]) - 0))/3;
ParaZ:=( abs(abs(ori[1,3]) - 0)+abs(abs(ori[2,3]) - 0)+abs(abs(ori[3,3]) - 1))/3;

if (abs(ParaZ)<=0.1) then
fprintf(output2,"%f %f %f\n", x, y, z):
end if:

if (abs(djac)<=0.0) and (abs(ParaZ)<=0.1) then
fprintf(output3,"%f %f %f\n", x, y, z):
end if:

if (abs(djac)>0.0) and (abs(ParaZ)<=0.1) then
fprintf(output4,"%f %f %f\n", x, y, z):
end if:

#end if:
end do:

fclose(input1):
fclose(output1):
fclose(output2):
fclose(output3):
fclose(output4):
Appendix D

ODE description

The aim of Appendix B is to summarise the main features that ODE offers; for a full reference please consult the original online document “Open Dynamics Engine User Guide” by Russell Smith (Smith04).

Rigid bodies
A rigid body has various properties from the point of view of the simulation. Some properties change over time:
- position vector \((x, y, z)\) of the body’s point of reference, currently the point of reference must correspond to the body’s centre of mass
- linear velocity of the point of reference, a vector \((v_x, v_y, v_z)\)
- orientation of a body, represented by a quaternion \((q_s, q_x, q_y, q_z)\) or a 3x3 rotation matrix
- angular velocity vector \((w_x, w_y, w_z)\)

Other body properties are usually constant over time:
- Mass of the body.
- Position of the centre of mass with respect to the point of reference. In the current implementation the centre of mass and the point of reference must coincide.
- Inertia principal matrix.

Conceptually each body has an x-y-z coordinate frame embedded in it, that moves and rotates with the body, as shown in (Fig. B.1).
The origin of this coordinate frame is the body’s point of reference. Some values in ODE (vectors, matrices, etc.) are relative to the body coordinate frame, and others are relative to the global coordinate frame.

The shape of a rigid body is not a dynamical property. It is only collision detection that cares about the detailed shape of the body.

**Integration**
The process of simulating the rigid body system through time is called integration. Each integration step advances the current time by a given step size, adjusting the state of all the rigid bodies for the new time value.

The ODE current integrator is very stable, but not particularly accurate unless the step size is small. For most uses of ODE this is not a problem; ODE behaviour still looks perfectly physical in almost all cases.

ODE uses a first order semi-implicit integrator. The “semi implicit” means that some forces are calculated as though an implicit integrator is being used, and other forces are calculated as though the integrator is explicit. The constraint forces (applied to bodies to keep the constraints together) are implicit, and the “external” forces (applied by the user, and due to rotational effects) are explicit. Now, inaccuracy in implicit integrators is manifested as a reduction in energy; in other words the integrator damps the system. Inaccuracy in explicit integrators has the opposite effect, it increases the system energy. This is why systems simulated with explicit first order integrators can explode.

**Force accumulators**
Between each integrator step, the user can call functions to apply forces to the rigid body. These forces are added to “force accumulators” in the rigid body object. When the next integrator step happens, the sum of all the applied forces is used to push the body around. The forces accumulators are set to zero after each integrator step.
Joints and constraints
ODE joint is a relationship enforced between two bodies so that they can only have certain positions and orientations relative to each other. This relationship is called a constraint. (Fig. B.2) shows three different constraint types.

![Figure B.2 – Three constraint types: ball-and-socket, hinge, slider](image)

Each time the integrator takes a step, all the joints are allowed to apply constraint forces to the bodies they affect. These forces are calculated such that the bodies move in such a way to preserve all the joint relationships.

Each joint has a number of parameters controlling its geometry. An example is the position of the ball-and-socket point for a ball-and-socket joint. The functions to set joint parameters all take global coordinates, not body-relative coordinates. A consequence of this is that the rigid bodies that a joint connects must be positioned correctly before the joint is attached.

Joints implemented in ODE (Fig. B.3):

- Classic
- Ball and socket
- Hinge
The fixed joint maintains a fixed relative position and orientation between two bodies, or between a body and the static environment. However, if the user needs two bodies to be glued together it is better to represent them as a single body.

Contact
The contact joint prevents body 1 and body 2 from inter-penetrating at the contact point (Fig. B.4). It does this by only allowing the bodies to have an “outgoing” velocity in the direction of the contact normal. Contact joints are created and deleted in response to collision detection. They can simulate friction at the contact by applying special forces in the two friction directions that are perpendicular to the normal.
Angular Motor
An angular motor (AMotor) allows the relative angular velocities of two bodies to be controlled. The angular velocity can be controlled on up to three axes, allowing torque motors and stops to be set for rotation about those axes (Fig. B.5). This is mainly useful in conjunction with ball joints.

Joint groups
A joint group is a special container that holds joints in a world. Joints can be added to a group, and then, when those joints are no longer needed, the entire group of joints can be very quickly destroyed with one function call. However, individual joints in a group cannot be destroyed before the entire group is emptied.

Collision handling
Collisions between bodies or between bodies and the static environment are handled as follows:

1. Before each simulation step, the user calls collision detection functions to determine what is touching what. These functions return a list of contact points. Each contact point specifies a position in space, a surface normal vector, and a penetration depth.
2. A special contact joint is created for each contact point. Each contact joint has properties like rigidity/softness and the friction present at the contact surface.

3. The contact joints are put in a joint “group”, which allows them to be added to and removed from the system very quickly. The simulation speed goes down as the number of contacts goes up, so various strategies can be used to limit the number of contact points.

4. A simulation step is taken.

5. All contact joints are removed from the system.

**Typical simulation code**

A typical simulation follows these steps:

1. Create a dynamics world.
2. Create bodies in the dynamics world.
3. Set the state (position, orientation etc.) of all bodies.
4. Create joints in the dynamics world.
5. Attach the joints to the bodies.
6. Set the parameters of all joints.
7. Create a collision world and collision geometry objects, as necessary.
8. Create a joint group to hold the contact joints.
9. Loop:
   1. Apply forces to the bodies as necessary.
   2. Adjust the joint parameters as necessary.
   3. Call collision detection.
   4. Create a contact joint for every collision point, and put it in the contact joint group.
   5. Take a simulation step.
   6. Remove all joints in the contact joint group.
10. Destroy the dynamics and collision worlds.

**Physics model**

*Friction Approximation*

The Coulomb friction model is a simple, but effective way to model friction at contact points. It is a simple relationship between the normal and tangential forces present at a contact point. The rule is:

\[ |f_r| \leq \mu |f_n| \]

where \( f_n \) and \( f_r \) are the normal and tangential force vectors respectively, and \( \mu \) is the friction coefficient. This equation defines a “friction cone”. If the total friction force vector is within the cone then the contact is in “sticking mode”, and the friction force is enough to prevent the contacting surfaces from
moving with respect to each other. If the force vector is on the surface of the cone then the contact is in “sliding mode”, and the friction force is not large enough to prevent the contacting surfaces from sliding. The parameter $\mu$ thus specifies the maximum ratio of tangential to normal force.

ODE’s friction models are approximations to the friction cone, for reasons of efficiency. There are currently two approximations to chose from:

1. The meaning of $\mu$ is changed so that it specifies the maximum friction (tangential) force that can be present at a contact, in either of the tangential friction directions. This is rather non physical because it is independent of the normal force, but it can be useful and it is the computationally cheapest option. Note that in this case $\mu$ is a force limit and must be chosen appropriate to the simulation.

2. The friction cone is approximated by a friction pyramid aligned with the first and second friction directions. A further approximation is made: first ODE computes the normal forces assuming that all the contacts are frictionless. Then it computes the maximum limits $f_m$ for the friction (tangential) forces from:

$$f_m = \mu |f_n|$$

and then proceeds to solve for the entire system with these fixed limits (in a manner similar to approximation 1 above). This differs from a true friction pyramid in that the "effective" $\mu$ is not quite fixed. This approximation is easier to use as $\mu$ is a unitless ratio the same as the normal Coloumb friction coefficient, and thus can be set to a constant value around 1.0 without regard for the specific simulation.

**Objects**

There are various kinds of object that can be created:

dWorld – a dynamics world. It is a container for rigid bodies and joints.
dSpace – a collision space. It can contain other geoms. It is similar to the rigid body concept of the “world”, except that it applies to collision instead of dynamics.
dBody – a rigid body.
dGeom – a geometry (for collision).
dJoint – a joint.
dJointGroup – a group of joints.
Simulation speed

Each joint removes a number of degrees of freedom (DoF) from the system. For example, the ball and socket removes three DoF, and the hinge removes five DoF. For each separate group of bodies connected by joints, where:
- $m_i$ is the number of joints in the group,
- $m_2$ is the total number of DoF moved by those joints, and
- $n$ is the number of bodies in the group,
then the computing time per step for the group is proportional to:

$$k_1O(m_i) + k_2O(m_2^3) + k_3O(n)$$

where $O$ stands for “order”.

ODE currently relies on factorization of a “system” matrix that has one row/column for each DoF removed (this is where the $O(m_2^3)$ comes from). In a 10 body chain that uses ball and socket joints, roughly 30-40% of the time is spent filling in this matrix, and 30-40% of the time is spent factorizing it.

Thus, to speed up the simulation the user might consider:
- Using less joints
- Replacing multiple joints with simpler alternatives.
- Using less contacts.
- Preferring frictionless or viscous friction contacts (that remove one DoF) over Coulomb friction contacts (that remove three DoF where possible).
Appendix E

ODE code

/* *******************************************************/
/* *** 0 CALL OF ODE LIBRARY *************/
/* *******************************************************/

/* exercise the C interface */
#include <stdio.h>
#include <ode/ode.h>
#include <drawstuff/drawstuff.h>

#ifdef _MSC_VER
#pragma warning(disable:4244 4305) // for VC++, no precision loss complaints
#endif

/* select correct drawing functions */
#ifdef dDOUBLE
#define dsDrawBox dsDrawBoxD
#define dsDrawSphere dsDrawSphereD
#define dsDrawCylinder dsDrawCylinderD
#define dsDrawCappedCylinder dsDrawCappedCylinderD
#endif

/* *******************************************************/
/* *** 2 CONSTANTS DECLARATION *************/
/* *******************************************************/
#define NUM 7 /* number of boxes */
#define SIDE (0.2) /* side length of a box */
#define MASS_L (1.0) /* mass of a box */
#define MASS_H (4.0) /* mass of a fixed body */
#define RADIUS (0.2f) /* serpent module: cupped cylinder radius */
#define HEIGH (0.2f) /* serpent module: cupped cylinder height */
#define RADIUS (0.7f) /* serpent module: cupped cylinder radius */
#define HEIGH (1.0f)    /* serpent module: cupped cylinder height */
#define RADIUS2 (0.1f)  /* organ radius */
#define RADIUS3 (0.2f)  /* axis of wheel: cylinder radius*/
#define HEIGH2 (0.6f)   /* axis of wheel: cylinder height */
#define RADIUS4 (2.0f)  /* wheel: cylinder radius*/
#define HEIGH3 (0.2f)   /* wheel: cylinder height */
#define RADIUSC (0.2f)  /* radius of the 8 small spheres */
#define WHEEL (1.0f)    /* cube wheel */
#define GATE_S (1.0f)   /* GATE SIZE */
#define GATE_T (0.5f)   /* GATE THICKNESS */
#define GATE_D (3.0f)   /* GATE POSITION Y */
#define SNAKE_Z (5.0f)  /* INIZIAL POSITION OF THE SNAKE */

static dSpaceID snake_space;
/* dynamics and collision objects */
static dWorldID world;
static dSpaceID space;
static dBodyID body[100];
static dJointID joint[NUM+2];
static dJointGroupID contactgroup;
static dGeomID CappedCylinder[NUM];
static dGeomID Cylinder[1];
static dGeomID box[40]; //leave 4 instead of 5?
static dGeomID sphere[3];
static dGeomID ground;
static dGeomID gate_1, gate_2, gate_3;
static dGeomID sphere_1, sphere_2, sphere_3, sphere_4;
static dGeomID sphere_5, sphere_6, sphere_7, sphere_8;
static dQuaternion q, s1, s2, s3;
static dQuaternion f1, f2, f3, f4, f5, f6, f7, f8;
static dReal x_mov=0.05f, y_mov=0.05f, z_mov=0.05f; // user commands
static dReal x_tot=2.0f, y_tot=3.0f, z_tot=RADIUS;

// state set by keyboard commands

/*************************/
/**** 0 SPACE COLLIDE (OF 2 OBJECTS) ****
/*************************/

static void nearCallback (void *data, dGeomID o1, dGeomID o2)
{
    int i,n;
    dBodyID b1,b2;

    //** if 2 objects are connected no collision
if (dGeomGetBody(o2) && dGeomGetBody(o2) && dAreConnected(dGeomGetBody(o1),dGeomGetBody(o2))) return;

//
// if (!((o1 == ground || o1 == gate_1 || o1 == gate_2 || o1 == gate_3) ^ (o2 == ground || o2 == gate_1 || o2 == gate_2 || o2 == gate_3))) return;

//if (!((o1 == ground || o1 == body[NUM+6] ) ^ (o2 == ground || o2 == body[NUM+6]))) return;

const int N = 100;
dContact contact[N];

b1 = dGeomGetBody(o1);
b2 = dGeomGetBody(o2);
if (b2 && b2 && dAreConnected (b1,b2)) return;

n = dCollide (o1.o2,N,&contact[0].geom,sizeof(dContact));
if (n > 0) {
    for (i=0; i<n; i++) {
        contact[i].surface.mode = dContactSlip1 | dContactSlip2 |
        dContactSoftERP | dContactSoftCFM | dContactApprox1;
        contact[i].surface.mu = dInfinity;
        contact[i].surface.slip1 = 0.1;
        contact[i].surface.slip2 = 0.1;
        contact[i].surface.soft_erp = 0.2; //0.5
        contact[i].surface.soft_cfm = 0.3;
        dJointID c = dJointCreateContact (world,contactgroup,&contact[i].);
        dJointAttach (c,
            dGeomGetBody(contact[i].geom.g1),
            dGeomGetBody(contact[i].geom.g2));
    }
}

/* start simulation - set viewpoint */

static void start()
{
    static float xyz[3] = {2.1640f,-1.3079f,1.7600f};
    static float hpr[3] = {125.5000f,-17.0000f,0.0000f};
    dsSetViewpoint (xyz,hpr);
    printf (“Press ‘e’ to start/stop occasional error.
”);
}

/**********************************************************/
/********       2 CONTROL KEYS DECLARATION  ************/
/**********************************************************/

static void command (int cmd)
{
    switch (cmd) {
    case 'z':
        x_tot = x_tot + x_mov;
        break;
    case 'x':
        x_tot = x_tot - x_mov;
        break;
    }
case 'a':
    y_tot = y_tot + y_mov;
    break;
  case 's':
    y_tot = (y_tot - y_mov);
    break;
  case 'q':
    z_tot = z_tot + z_mov;
    break;
  case 'w':
    z_tot = (z_tot - z_mov);
    break;
}
}

/* simulation loop */

static void simLoop (int pause)
{
  int i;
  if (!pause) {
    /*-----------------------------*/
    /*      5 REAL TIME CONTROL    */
    /*-----------------------------*/
    static double angle = 0;
    angle += 0.01;
    //dBodyAddForce (body[NUM-1],0.5*(sin(1*angle)+1.0),0.5*(sin(1*angle)+1.0),0.02);
    //dBodyAddForce (body[NUM-1],x_tot*1,y_tot*1,z_tot*1);
    //dBodySetPosition (body[NUM-1],1*(sin(angle)) ,3.5, 0.0);
    // hand driven cube position
    //dBodySetPosition (body[NUM-1],x_tot*1,y_tot*1,z_tot*1);
    //dBodySetPosition (body[NUM-1],x_tot*1,y_tot*1,z_tot*1);
    dBodySetPosition (body[NUM-1],x_tot,y_tot,z_tot);
    dSpaceCollide (space,0,&nearCallback);
    dWorldStep (world,0.05);
    /* remove all contact joints */
    dJointGroupEmpty (contactgroup);
  }
  /*-----------------------------*/
  /*    4 VISIBLE OBJECTS DURING SIMULATION    */
  /*-----------------------------*/

  //serpent module
  dsSetColor (1,1,0);
  dsSetTexture (DS_WOOD);
  for (i=0; i<NUM; i++) dsDrawCappedCylinder (dBodyGetPosition(body[i]),
                                             dBodyGetRotation(body[i]),HEIGH,RADIUS );

  //cube driven by hand
  dsSetColor (1,1,2);
  dReal sides[3] = {0.3,0.3,0.3};
  dsDrawBox (dBodyGetPosition(body[NUM]),dBodyGetRotation(body[NUM]),sides);
// cylinder-sphere axis of wheel (has a shape of a cylinder)
 dsSetColor (0.1,1.1);
 dsDrawCylinder (dBodyGetPosition(body[NUM+1]),
 dBodyGetRotation(body[NUM+1]),HEIGH2,RADIUS3);

// sphere organ
 dsSetColor (1.2,0);
 dsDrawSphere (dBodyGetPosition(body[NUM+5]), dBodyGetRotation(body[NUM+5]),RADIUS2);

// cylinder-sphere wheel (has a shape of a cylinder)
 dsSetColor (2,0,0);
 dsDrawCylinder (dBodyGetPosition(body[NUM+6]),
 dBodyGetRotation(body[NUM+6]),HEIGH3,RADIUS4);

// blue gate
 dsSetColor (0,0,2);
 dGeomBoxGetLengths (gate_1,s1);
 dsDrawBox (dGeomGetPosition(gate_1),dGeomGetRotation(gate_1),s1);
 // dGeomBoxGetLengths (gate_2,s2);
 dsDrawBox (dGeomGetPosition(gate_2),dGeomGetRotation(gate_2),s2);
 // dGeomBoxGetLengths (gate_3,s3);
 dsDrawBox (dGeomGetPosition(gate_3),dGeomGetRotation(gate_3),s3);

// 8 spheres
 /dsSetColor (1.1,0);
 /dsDrawSphere (dGeomGetPosition(sphere_1),dGeomGetRotation(sphere_1),RADIUSC);
 /dsDrawSphere (dGeomGetPosition(sphere_2),dGeomGetRotation(sphere_2),RADIUSC);
 /dsDrawSphere (dGeomGetPosition(sphere_3),dGeomGetRotation(sphere_3),RADIUSC);
 /dsDrawSphere (dGeomGetPosition(sphere_4),dGeomGetRotation(sphere_4),RADIUSC);
 /dsDrawSphere (dGeomGetPosition(sphere_5),dGeomGetRotation(sphere_5),RADIUSC);
 /dsDrawSphere (dGeomGetPosition(sphere_6),dGeomGetRotation(sphere_6),RADIUSC);
 /dsDrawSphere (dGeomGetPosition(sphere_7),dGeomGetRotation(sphere_7),RADIUSC);
 /dsDrawSphere (dGeomGetPosition(sphere_8),dGeomGetRotation(sphere_8),RADIUSC);

int main (int argc, char **argv)
{
  int i;
  dReal k;
  dMass m;

  /********************************************************************/
  /** 0 CALL OF ODE LIBRARY **/
  /********************************************************************/

  "" setup pointers to drawstuff callback functions ""
  dsFunctions fn;
  fn.version = DS_VERSION;
  fn.start = &start;
  fn.step = &simLoop;
  fn.command = &command;
  fn.stop = 0;
  fn.path_to_textures = "./drawstuff/textures";

  /********************************************************************/
  /** 1 WORLD CREATION **/
  /********************************************************************/

  world = dWorldCreate();
  space = dHashSpaceCreate (0);
contactgroup = dJointGroupCreate (10000);
dWorldSetGravity (world,0,0,-0.5);
//dCreatePlane (space,0,0,1.0);
ground = dCreatePlane (space,0,0,1.0);

// worm modules
for (i=0; i<NUM; i++) {
    body[i] = dBodyCreate (world);
    k = (RADIUS + RADIUS + HEIGH);
    dQFromAxisAndAngle (q,1,0,0,3.14*0.5);
dBodySetQuaternion (body[i],q);
dBodySetPosition (body[i],RADIUS4,k*i,0.5);
dMassSetBox (&m,1,0.1,0.1,0.3);
dMassAdjust (&m,0.5);
dBodySetMass (body[i],&m);
CappedCylinder[i] = dCreateCCylinder (0,RADIUS,HEIGH);
dGeomSetBody (CappedCylinder[i],body[i]);
}

for (i=0; i<(NUM-1); i++) {
    joint[i] = dJointCreateBall (world,0);
dJointAttach (joint[i],body[i],body[i+1]);
    k = (RADIUS + RADIUS + HEIGH);
    dJointSetBallAnchor (joint[i],RADIUS4,k*0.5+k*i,0.5);
}

//axis of wheel
body[NUM+1] = dBodyCreate (world);
dBodySetPosition (body[NUM+1], 0.0, 0.0, SIDE/2);
//dQFromAxisAndAngle (q, 1, 0, 0, 0); //dRFromEulerAngles (q, 0, 0, 0); //dQSetIdentity (q);
//dQFromAxisAndAngle (q,0,0,0,M_PI*0.5);
//dBodySetQuaternion (body[NUM+1],q);
dMassSetBox (&m,1.2,0.2,0.0,1);
dMassAdjust (&m,10);
dBodySetMass (body[NUM+1],&m);
box[2] = dCreateBox (0, 3.0,3.0,0.1);
dGeomSetBody (box[2],body[NUM+1]);

//wheel
body[NUM+6] = dBodyCreate (world);
dBodySetPosition (body[NUM+6], 0.0, 0.0, 0.0);
dMassSetBox (&m,1,SIDE,SIDE,SIDE);
dMassAdjust (&m,0.1);
dBodySetMass (body[NUM+6],&m);
box[3] = dCreateBox (0, 0.8,0.8, HEIGH2);
dGeomSetBody (box[3],body[NUM+6]);
//sphere[2] = dCreateSphere (0, RADIUS4);
//dGeomSetBody (sphere[2],body[NUM+6]);

// sphere: organ
body[NUM+5] = dBodyCreate (world);
dBodySetPosition (body[NUM+5], RADIUS4, 0.0, 0.0);
dMassSetBox (&m,1,SIDE,SIDE,SIDE);
dMassAdjust (&m,0.1);
dBodySetMass (body[NUM+5],&m);
sphere[1] = dCreateSphere (0, RADIUS2);
dGeomSetBody (sphere[1],body[NUM+5]);

//link axis of wheel - wheel
joint[NUM] = dJointCreateHinge (world,0);
dJointAttach (joint[NUM], body[NUM+1], body[NUM+6]);
dJointSetHingeAnchor (joint[NUM], 0.0, 0.0, 0.0);
dJointSetHingeAxis (joint[NUM], 0.0, 0.0, 0.1);

// link wheel - organ
joint[NUM+1] = dJointCreateBall (world, 0);
dJointAttach (joint[NUM+1], body[NUM+6], body[NUM+5]);
dJointSetBallAnchor (joint[NUM+1], RADIUS4, 0.0, 0.0);

// link organ - worm
joint[NUM+2] = dJointCreateBall (world, 0);
dJointAttach (joint[NUM+2], body[1], body[NUM+5]);
dJointSetBallAnchor (joint[NUM+2], RADIUS4, 0.0, 0.0);

snake_space = dSimpleSpaceCreate (space);
dSpaceSetCleanup (snake_space, 0);
for (i=0; i<NUM; i++) {
    dSpaceAdd (snake_space, CappedCylinder[i]);
}
dSpaceAdd (snake_space, box[2]);
dSpaceAdd (snake_space, sphere[1]);
dSpaceAdd (snake_space, box[3]);

// moving cube; by hand
body[NUM] = dBodyCreate (world);
dBodySetPosition (body[NUM], -4.0, 0.0, 10.0);
dMassSetBox (&m, 1, SIDE, SIDE, SIDE);
dMassAdjust (&m, MASS_L);
dBodySetMass (body[NUM], &m);
box[1] = dCreateBox (space, 0.1, 0.1, 0.1);
GeomSetBody (box[1], body[NUM]);

// blue solid gate
gate_1 = dCreateBox (space, GATE_T, GATE_T, GATE_S);
dGeomSetPosition (gate_1, GATE_S*0.5 + GATE_T*0.5, GATE_D, GATE_S*0.5);
//
gate_2 = dCreateBox (space, GATE_T, GATE_T, GATE_S);
dGeomSetPosition (gate_2, -(GATE_S*0.5 + GATE_T*0.5), GATE_D, GATE_S*0.5);
//
gate_3 = dCreateBox (space, GATE_T, GATE_T, GATE_S);
dGeomSetPosition (gate_3, 0.0, GATE_D, GATE_S*1 + GATE_T*0.5);
//
// sphere_1 = dCreateSphere (space, GATE_T, GATE_T, GATE_T);
// dGeomSetPosition (sphere_1, GATE_D, GATE_S*1 + GATE_T*0.5);

// sphere park
sphere_1 = dCreateSphere (space, RADIUS_K);
dGeomSetPosition (sphere_1, RADIUS4 - RADIUS_K, 0.0, 2*RADIUS_K);
//
sphere_2 = dCreateSphere (space, RADIUS_K);
dGeomSetPosition (sphere_2, (RADIUS4 - RADIUS_K)*0.7071, (RADIUS4 - RADIUS_K)*0.7071, 2*RADIUS_K);
//
sphere_3 = dCreateSphere (space, RADIUS_K);
dGeomSetPosition (sphere_3, 0.0, RADIUS4 - RADIUS_K, 2*RADIUS_K);
//
sphere_4 = dCreateSphere (space, RADIUS_K);
dGeomSetPosition (sphere_4, -(RADIUS4 - RADIUS_K)*0.7071, (RADIUS4 - RADIUS_K)*0.7071, 2*RADIUS_K);
//
sphere_5 = dCreateSphere (space, RADIUS_K);
dGeomSetPosition (sphere_5, -(RADIUS4 - RADIUS_K), 0.0, 2*RADIUS_K);
Appendix E

```c
        //
        //    sphere_6=dCreateSphere (space,RADIUSC);
        //    dGeomSetPosition (sphere_6, -(RADIUS4-RADIUSC)*0.7071, -(RADIUS4-RADIUSC)*0.7071, 2*RADIUSC);
        //
        //    sphere_7=dCreateSphere (space,RADIUSC);
        //    dGeomSetPosition (sphere_7, 0.0, -(RADIUS4-RADIUSC), 2*RADIUSC);
        //
        //    sphere_8=dCreateSphere (space,RADIUSC);
        //    dGeomSetPosition (sphere_8, +(RADIUS4-RADIUSC)*0.7071, -(RADIUS4-RADIUSC)*0.7071, 2*RADIUSC);
        
        /***********************************************************/
        /****           0 RUN SIMULATION               *************/
        /***********************************************************/
        // run simulation
        dsSimulationLoop (argc,argv,352,288,&fn);
        dJointGroupDestroy (contactgroup);
        dSpaceDestroy (space);
        dWorldDestroy (world);
        /*dGeomDestroy (box[0]);
        dGeomDestroy (sphere[0]);
        dGeomDestroy (sphere[1]);
        dGeomDestroy (sphere[2]);*/

        return 0;
```