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Miniature gripping device

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Abstract

Teleoperation is a relatively old practice; recently new fields of intervention are born where the slave arms need to have small dimensions and high dexterity; examples are pipes inspection, rescue missions, planets exploration, minimally invasive surgery. The object of the paper is to describe the design of a miniature gripper suitable for laparoscopic operations. First some possible solutions are analyzed 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 have been pointed out. Finally some possible system implementations are suggested.

1 Introduction

Scientific communities, Universities and some of the most important research laboratories believe that medical robotics is a key field of research. Different applications exist: from eye surgery, to abdominal surgery, to prostheses and colonoscopies. Long since that robotic systems are used inside surgery rooms for minimally invasive robotic surgery (MIRS) operations. The task of the robot is not to replace the surgeon, but to support him with a set of instruments that simplify the procedures and to reduce the patient trauma.

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

MIRS instruments, like grippers and scissors, need to be as compact as possible. The arm and the end effector actuation should be decoupled to simplify the control; to achieve this task, the actuator is positioned close to the instrument. As a further constraint, in case of grippers, the actuator should be able to exert the forces of several tens of Newtons. The scope of the article is to propose some innovative MIRS grippers.

2 Proposed solutions

One of the most difficult operations, due to the lack of dexterity of conventional systems, is suturing with needle and wire; the arms with grippers have to mime the movements of the surgeon fingers.

The main specifications for the proposed gripper are: 40 N grasping force, 10 mm external diameter, about 25 mm length, possibility to work in an humid environment, high reliability and body compatibility. We have chosen to reject the cable actuation, despite it is widely used in the surgical field, for two reasons; it is difficult to embed the cables inside a poli-articulated miniature arm. Besides the cable actuation, high grasping force, can affect the global rigidity of the arm [1] [2].

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

2.1 Electric motors solution

Initially it has been chosen to drive the gripper with classic electric mini-motors; the motors (fig. 1, part 1) are coupled with planetary reducers (fig. 1, part 2) to increase the torque. Conic gears (fig. 1, part 3) transfer the motion to the jaws (fig. 1, part 4). A detail view of the jaw is reported in the figure 1; 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.

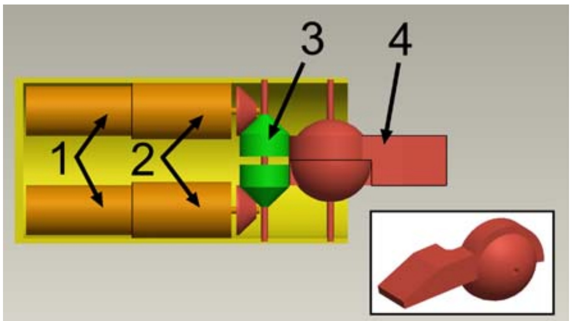

Figure 1. Gripper actuated by electric motors I

The jaws can be independently actuated; this embodiment, having two DoF, 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) [3].

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 ∅ 3 mm conic gear is difficult, and the forces generated by this kind of motor are not sufficient for a firm grasp.

A second motorised gripper is now illustrated (fig.2). An electric motor (fig. 2, part 1), coupled with a gearbox (fig. 2, part 2), drives a worm and nut transmission (fig. 2, part 3 and 4). The step of the worm can be reduced to increase the transmission rate. The nut is coupled with two jaws; for clarity reasons, figure 2 shows only one of the two jaws.

This solution presents the advantage to be not reversible. However the drawback of miniature electric motors is low torque/volume ratio.

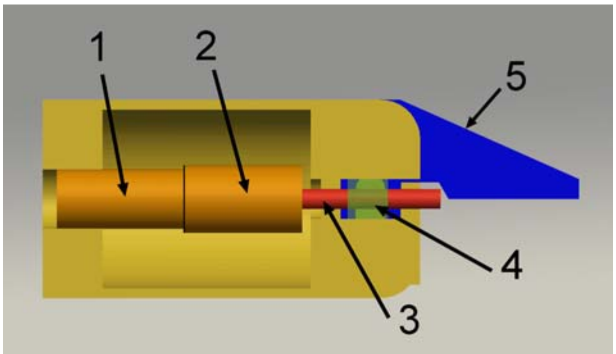

Figure 2. Gripper actuated by electric motors II

2.2 Hydraulic piston

We propose a basic scheme for the hydraulic actuation. The fluid enters from a door (fig. 3, part 1) into a chamber (fig. 3, part 2). Inside the chamber slides a piston (fig. 3, part 4); an o-ring avoids the fluid leach (fig. 3, part 3). The piston drives a shaft on which is linked a pin (fig. 3, part 6). The pin moves both the jaws (fig. 3, part 7). A spring (fig. 3, part 5) produces the closure motion.

As recalled before, fluid feeding complicates the arm architecture. A similar scheme is proposed by Peirs [4].

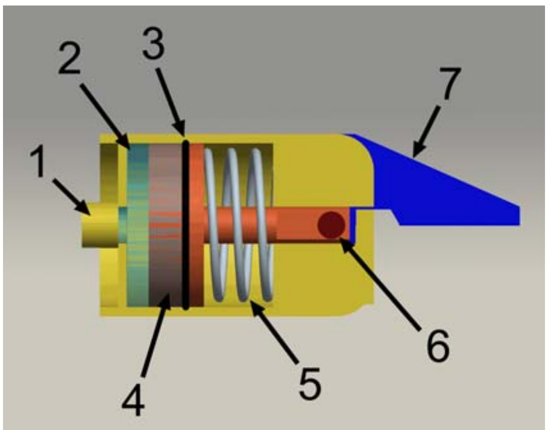

Figure 3. Hydraulic gripper

This solution presents the advantage of simplicity and reliability but the need of fluid supply cable inside the arm, the pressurised fluid an cleaning problems advise against its application.

2.3 Shape memory alloy

SMA and in particular NiTiNol can be easily integrated as actuators inside miniature grippers; some designs are now proposed.

2.3.1 Two ways memory shape effect

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 [5]. Figure 4 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, part 1) or curved (fig. 6, part 2).

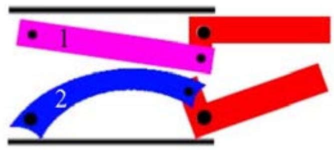

Figure 4. TWMSE gripper

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 [6].

It has been therefore chosen to use only SMA with one way memory shape effect (OWMSE).

2.3.2 SMA springs

Figure 5 shows a gripper powered by a popular SMA linear transducer; a SMA spring provides forward motion (fig. 5, part 1), backward movement is given by a steel spring (fig. 5, part 2).

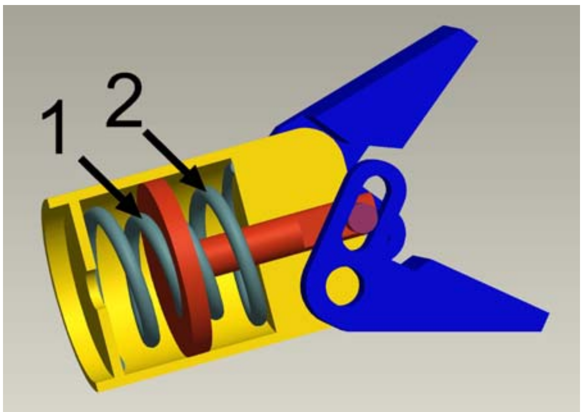

Figure 5. SMA spring gripper

A rich literature describes this kind of linear actuator [7]. For our specific problem, 40 N gripping force, the size of the SMA spring results too big to be embedded inside the instrument, moreover the cooling time of such a NiTiNol spring is too long for the surgical procedures.

2.3.3 SMA wires

This solution adopts SMA wires. Tipically for a shortening from 3% to 5% their life cycle is 10E5 [6] [8]. A set of SMA wires (fig. 6, part 1) disposed in parallel opens the jaw of the gripper (fig. 6 part 2); the closure is provided by a steel spring (fig. 6, part 3).

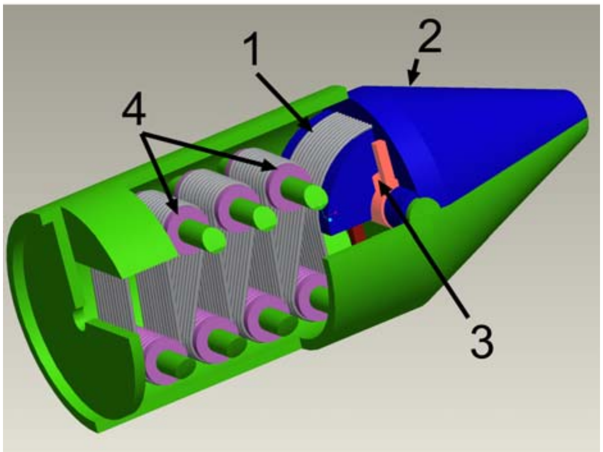

Figure 6. Gripper with SMA wire for opening

The SMA clamp has only one jaw instead of two, this choice simplifies the clamp design and enhances the grasping accuracy. 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 we want the needle not to move during the grasping procedure, the needle should be centred respect to the axis of the gripper. The shortening of the wires is only 4%; several pulleys (fig. 6, 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.
This solution will be described in detail in the following section.

3 Preferred design

From a comparison between the proposed solutions, presented in the previous section, the SMA wires gripper has been selected; this solution is compact, exerts sufficient forces and has a relatively simple architecture.

Further considerations leaded to change slightly the original design. Solution 2.3.3, uses a steel spring, like a clothes peg, to close the gripper and 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 2.3.3) is big to exert the needed closure force, the spring used for opening is small because it has only the task to stretch cool 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. This effect increases the cooling time of the wires lowering the gripper opening speed. Figure 7 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.

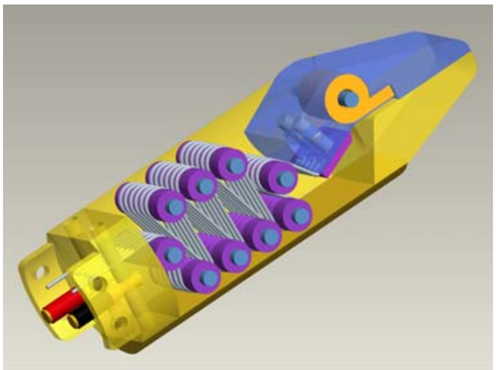

Figure 7. Gripper with SMA wire for closure

The size and position of the pulleys has been optimised to maximise the length of the SMA wires (fig. 8). Each SMA wire is 67 mm long and opens the jaw 30°.

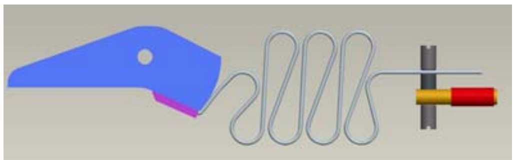

Figure 8. Arrangement of SMA wire

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 teeth shaped to avoid contact between the adjacent 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. 9).

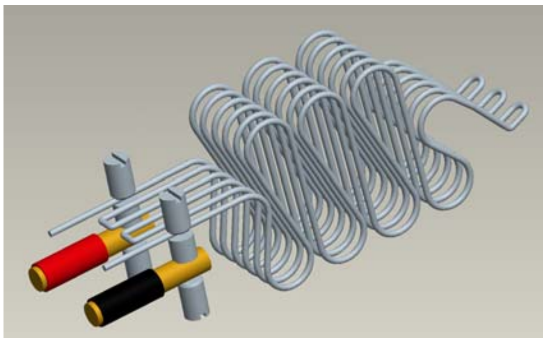

Figure 9. SMA wires

Figure 10 shows the link between the SMA wire and the jaw; the wire (fig. 10, part 2) is disposed around three pins (fig. 10, part 1) fixed on the jaw. An isolating plate (fig. 10, part 3), connected by two M1 screws (fig. 10, part 4), keeps the wires in the right position.

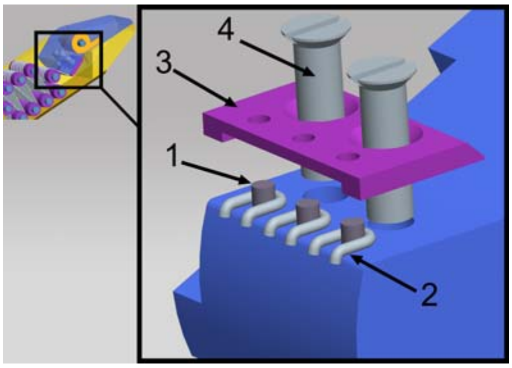

Figure 10. SMA wires link detail

A tensioning system allows to gain the wire clearance lost during the assembly phase (fig. 11). Each SMA wire end (fig. 11, part 1) is electrically connected with the gripper electric plug (fig. 11, part 5). Two screws (fig. 11, part 3 and 4) secure these components to a conductive element (fig. 11, part 2).

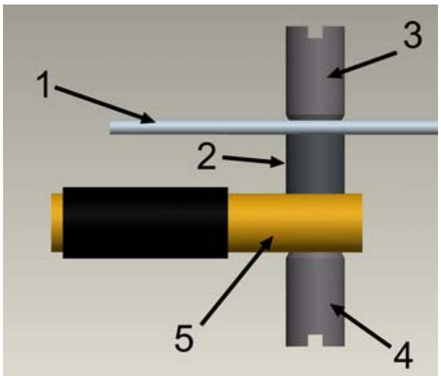

Figure 11. Wire tensioning system

This system fixes mechanically the SMA wires; in fact SMA material, if welded, looses its "memory". The overall length of the wire is about 0,420 m, its resistance is 20 Ω/m, the suggested electric current is 1000 mA; the grippers then need 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. 12).

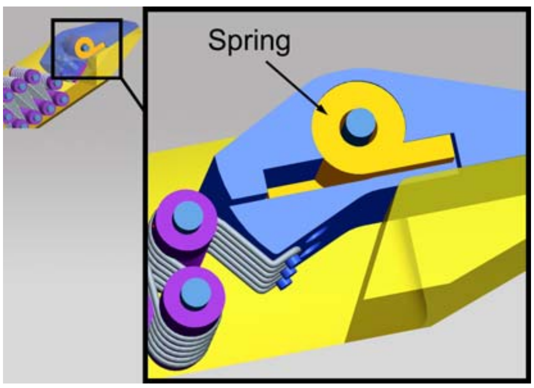

Figure 12. Jaw detail

The ∅ 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.

4 Dimensioning of the gripper

The dimensioning of the preferred solution 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 13 gives a schematic view of the gripper static model.

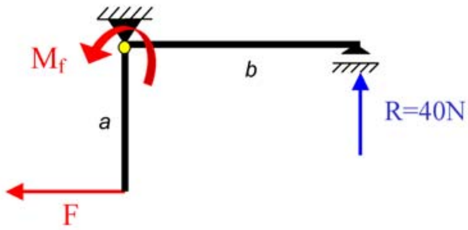

Figure 13. Force schema

The force "F" generated by the wires, is function of the gripper geometry: $F = \frac{b}{a} R$ (1)

The overall force "F" is obtained by the contribution of "n" wires having each a force "F_i": $F = nF_i$ (2)

The length "L" of each wire depends on two parameters: the opening angle of the gripper "φ" and the arm "a" length: $L = \frac{a \cdot \varphi}{4\%}$ (3)

The shortening of "L" is 4%. The influence of the length "a" is now analysed; it is better to have a long "a" to exert higher forces "F" with the same number of wires (equation 1), but at the same time, a short "a" reduces the length of the SMA wire (equation 3). A limited number of long wires simplifies the assembly ("a" high). The parameters can vary as follows:

$5 \text{ mm} \le b \le 10 \text{ mm}$, $1 \text{ mm} \le a \le 5 \text{ mm}$

$30° \le \varphi \le 60°$, $1 \le n \le 10$

The following table shows the specifications of the commercial NiTiNol wire from Mondotronics [9].

SMA wire specifications			
Wire ∅ (mm)	0,254	0,30	0,375
F_i force generated (N)	9,12	12,26	19,61
G_i restore force (N)	1,6856	2,4010	3,8514

By applying an heuristic optimisation procedure, taking into account the gripper model, the SMA wire characteristics and geometry constraints the following parameters have been selected;

R=40 N (specification), L=67 mm (geometry)
wire ∅=0,254mm, b=5mm, a=5mm, $\varphi = 30°$.

The resulting number of wires is 6.

The force "G" of the spring is necessary to restore "n" SMA wires: $G = n \cdot G_i$ (4)

Using the 0.254 mm diameter wire and n=6 we obtain:
$G = 6 \cdot 1.69 = 10.14N$

The bending moment of the spring is:

$$M_f = G \cdot a = 50.7Nmm \quad (5)$$

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 $M_{f\,max}$. When the jaw is closed, the spring moment decreases. The spring is now dimensioned; as hypothesis the torsion spring is loaded only by a bending load. The wire diameter is:

$$d = \sqrt[4]{\frac{64 M_{f\,max} i D}{E\varphi}} \quad (6)$$

where:
i= number of coils; d=wire diameter of the spring;
D=spring diameter; φ=preload angle; E=Young's modulus.

Figure 14 shows a comparison of the two SMA actuations; SMA for closure (solution 2.3.3) and SMA

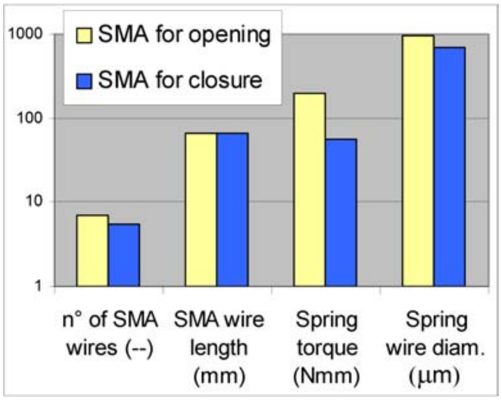

Figure 14. Comparison between two solutions

for opening (preferred solution), the following parameters have been fixed: R=40 N (specification), wire ∅=0,254mm, a=5mm, b=5mm, $\varphi = 30°$.

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).

5 Physical mock-up

A physical mock-up has been produced to verify the working principle of the gripper (fig. 15). 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 0.12mm ∅ SMA wires to reduce the assembly problems; the transition temperature of the wire is 130 °C. Inside the wood jaw is located a steel spring (fig. 16). Teflon pulleys offer electric insulation, low friction and high melting fusion.

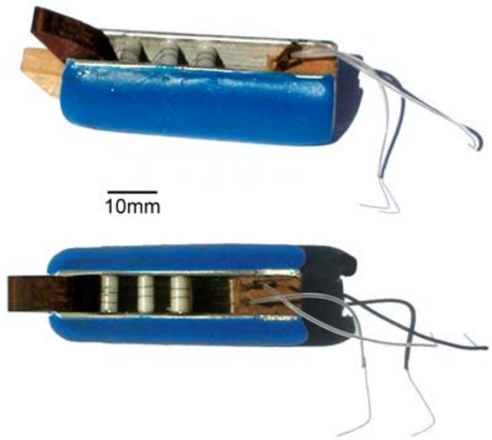

Figure 15. Early physical mock-up

Figure 16. Jaw and spring

The device, powered by 7 V @ 200 mA (fig. 17), creates a force of 3 N; in a 24 °C environment (natural convection), the bandwidth is about 0,5 Hz. SMA migrates gradually from the martensitic to austenitic phase; this transformation suffers hysteresis. To overcome these problems the literature proposes different non linear algorithms for the control of SMA actuators [10] [11] [12] [13]. We are working at the feasibility of a new control solution.

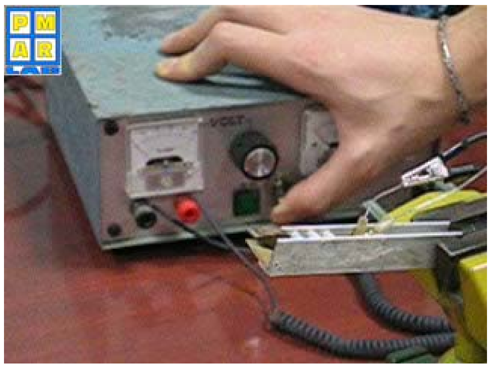

Figure 17. Physical mock up actuation

6 Conclusion

The designs of several miniature grippers have been presented and compared. The preferred solution is actuated by SMA wires; the design is compact, grasping forces are satisfy the specifications.

A physical mock-up has been built to validate the gripping performance. The prototype tested is a

simplified version of the preferred solution; future developments will include the realisation of a prototype identical to the preferred solution. The rig will give information about the real SMA cooling time (this information is difficult to compute theoretically).
The gripper bandwidth can be increased blowing on the SMA wires the CO_2 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 [14] [15].
Despite the gripper is born from surgery needs, the device can be employed even in other fields such as microassembly, samples acquisition, subsea robotics, space survey and biological labs.

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