An active tubular polyarticulated micro-system for flexible endoscope

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Abstract: This paper describes an original active steering device for endoscopes and boroscopes. Its mechanical structure is based on a tubular hyper-redundant mechanism. Distributed SMA actuators with their own local controller are integrated in this structure for producing bending forces in reaction to the interaction detected between the instrument and its environment.

The SMA actuators are two thin NiTi springs in an antagonist configuration. Joint actuation relies on martensite/austenite phase transformation in NiTi alloys. The global behavior of the endoscope is controlled through a multi-agent approach.

1. Introduction

Current instruments for endoscopy suffer from limitations mainly caused by the lack of mobility and ability to perform maneuvers into very small and geometrically complex 3D spaces.

An endoscope is a long thin tubular device for non-invasive inspection in interior cavities, canals, vessels, etc... inserted through a natural or surgically produced orifice. A typical outer diameter of endoscopes is 10 mm and their length varies from 70 to 180 mm. The endoscope body contains several light guides (typically 2), tool channels (biopsy grippers, snare, cytology brush) and optics or electronics for the image transmission. Endoscopes can be rigid or flexible. The latter use optical fiber bundles for image transmission to the headset. The user can view the image transmitted by the instrument directly through an eyepiece or, when a camera is connected to the headset, the image displayed on a monitor. This arrangement is called indirect video endoscopy. When a CCD chip is integrated in the distal part, the image is electronically transmitted, it is direct (or distal) video endoscopy.

A steerable tip can be mounted on most of these instruments. The change of the tip orientation facilitates the endoscope progression in cavities and also modifies the viewing direction. This passively bendable part is generally deflected by one or two pairs of cables (depending upon the number of planes of bending) connected to a remote control mechanism located close to the headset.

Similar non-medical devices (boroscopes) are used for internal visual inspection of highly integrated mechanical systems such as jet engines or satellites. The boroscope must be insertable into narrow cooked passageways, the associated progression difficulties paralleling those of endoscopes.

These devices, while highly flexible, have limited steering ability. They cannot traverse tight bends nor negotiate complexe interior structures. As a consequence, for instance about 60% of the gastro-intestinal track is unreachable with current endoscope technology. Moreover, one of the major risk with these instruments is the perforation of the patient's tissues due to their substantial stiffness. There are also problems which results from excessive stresses applied on the operating cables, they frequently break or acquire a permanent strain.

In addition, the trend is to move towards smaller and smaller diameter endoscopes required by applications such as neuro-surgery, cardio-vascular-surgery or obstetrical procedures and this can not be tackled by a scale reduction of the current technologies.

This paper describes the design of a mechanical system and a distributed actuation system with a self-guiding control strategy for a scalable steering device able to dexterously maneuver through small and geometrically complex 3D structures.

Very few devices of this kind can be found in the scientific literature [1, 2, 3] but some are described in patents [4, 5]. They relate generally on shape memory alloy (SMA) distributed films integrated control drivers deposited on a flexible substrate and integrated using VLSI techniques.

2. Design principles and system description

The device has been designed to give the user more dexterity in endoscopic procedures than with current instruments. It means to provide an endoscope system which can be easily inserted deep into the body cavity to be inspected while minimizing the risk for perforation of organ walls or damaging the instrument (cable stretching or breaking).

Here, technology is a key issue. It is clear that cables is no longer a solution for getting tight bends in 3D space. The outer diameter has to be as small as possible considering that the room needed for optical fibers bundles and chanels for surgical tools and fluids, which defines the inner diameter, can not be reduced. Another important feature is that the bending force required for a given stiffness of the inner components increases when reducing the endoscope diameter. Moreover, the technology selection must withstand the sterilization process (140^{o}C during 20 minutes). It has to make the system as simple as possible and to facilitate its manufacturing at small scale.

The controllably bendable portion of the instrument must be able to adapt its local curvature to the interior geometry by a spontaneous reaction to the interactions with the environment while the viewing tip follows a track in a vessel or in a cavity.

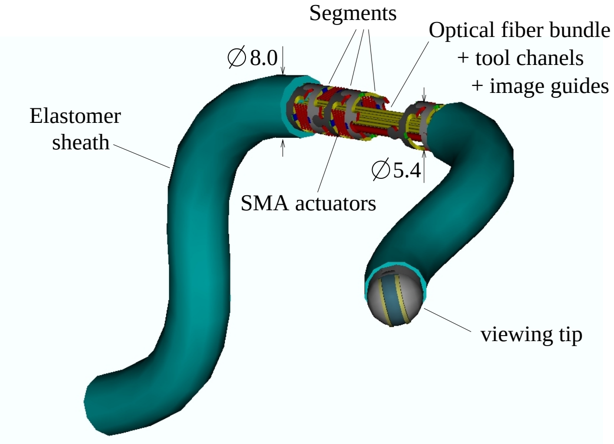


Figure 1. Schematic view of the steering device

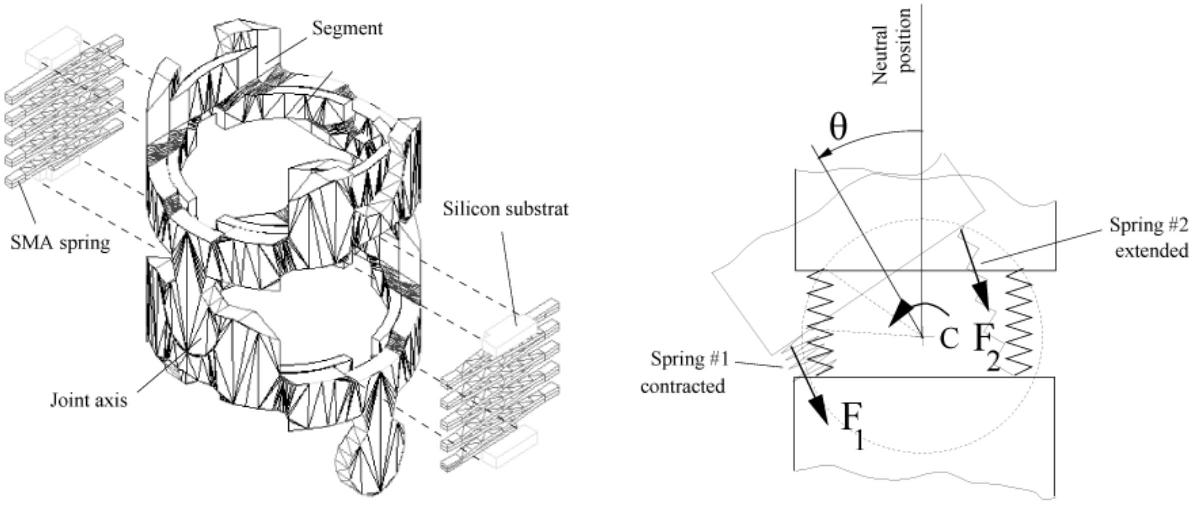
Figure 1 schematically illustrated the endoscopic system we designed. The mechanical structure of the device can be viewed as an hyper-redundant manipulator which embrace the endoscope components (optic bundle, light guides, tool chanels). It is a serial arrangement of tubular segments articulated to each other by pin joints. This design is modular, the number of segments can be adjusted to the application and is in theory infinite. On the actual design, the segment length is 4 mm, the inner diameter 5.4 mm and the outer diameter (including the outer elastomer cover) is 8 mm. The distal viewing tip integrates a variable field optical system comprising an image guide, objective and rotatable prism actuated by a polymer gel actuator. This enable to obverse continuously over a wide range inside narrow body cavities or tubes without removing the endoscope for replacing the distal end type.

This system is usually protected by a metallic sheath in industrial endoscopes and/or by a flexible polymer sheath in medical endoscopes. Notice that this sheath significantly increases the strength requirements for the bending actuators.

3. A tubular hyper-redundant manipulator

The hyper-redundant manipulator is composed of identical modules (iron rings) linked together by pin joints whose axes are alternatively oriented at 90^o in the same plane. This mechanical design allows to bend the endoscope body along complex curves in the 3-D space.

The modules are obtained by an electro-erosive processing technique. By using this substractive manufacturing method, joints and links are made in one piece. The pin and the hinge are respectively the positive and the negative cutting in the cylindrical shell of the segment. The relative translation of two consecutive modules along the joint axis is suppressed by inserting a very thin internal ring has shown on figure 2-a. The steering mechanism is assembled by simply plugging these segments whose length can be reduce to 4 mm such that a 15 mm curvature radius can be achieved.



a- SMA actuators integration

b- Joint bending

Figure 2. Joint description

Two spring-like actuators are integrated with their own control circuit in each module to change the relative orientation of two consecutive segments. These actuator are Shape Memory Alloy (SMA) springs mounted in an antagonist configuration.

The actuator is controlled by the electrical power supplied to the SMA. A control circuit is associated to each actuator. It is integrated on a substrate of alumina by using hybrid electronic technologies.

4. SMA actuator design

The SMA actuator elements are springs cut out by photochemical etching process in a NiTi (Nickel-Titanium) ribbon (Figure 3-a).

Basically, these SMA actuators undergo a micro-structural transformation from their austenite phase to their martensite phase [6]. This phase transformation can be activated by heating and cooling the material or by applying an external stress.

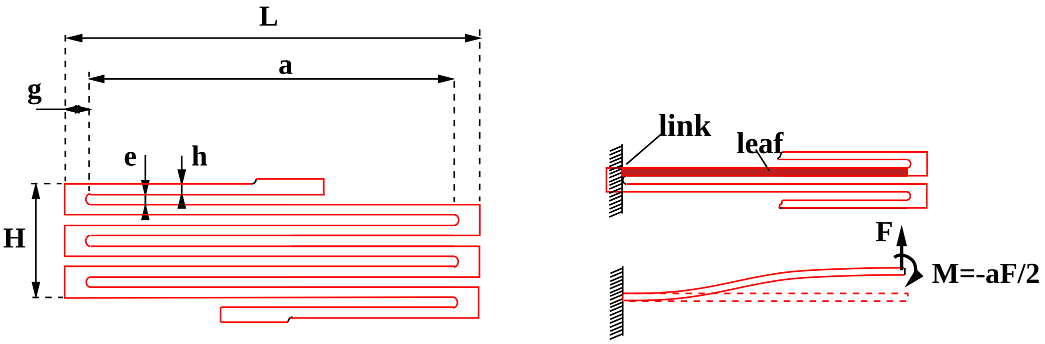


Figure 3. SMA spring description

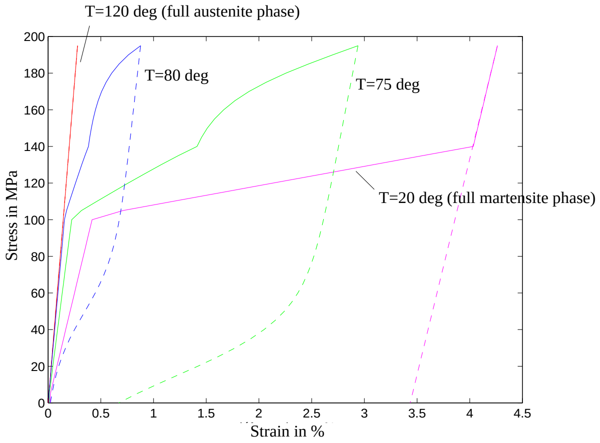


Figure 4. Strain-stress diagram of the NiTi (50%-50%) alloy

For a 50%-50% NiTi alloy, as the one used here, the transition temperatures are $A_s = 40^o$ and $M_s = 70^o$ for a null applied constraint to the material.

This phase transformation also induces a large modification in the material Young's modulus (Figure 4). This property is exploited here to create unballanced pulling forces applied by the two antagonist SMA springs. This results in an output joint torque (Figure 3-b). The mapping between the spring pulling forces and the output torque is joint configuration dependent and hightly non-linear.

SMA actuators design has to take into account dimensional constraints and deflexion resistance of the endoscope.

Resistance to deflexion, due to the endoscope body and the outer elastomer sheath, was experimentally evaluated. On Figure 5, we represented the necessary output joint torque to bend a rotoïd axis in an existing endoscope. For deflexions smaller than 15^o, the resistive torque is about $0.01Nm$.

The SMA spring on Figure 3-a can be approximated by an assembly of flexible parts (leaves of length a) linked by rigid parts. For symetrical reasons,

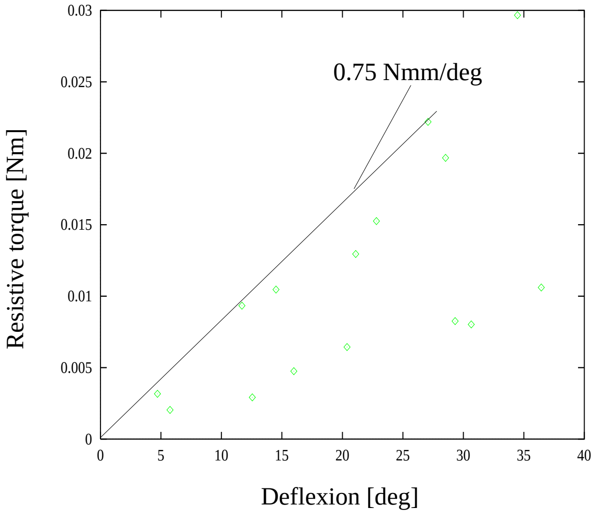


Figure 5. Resistive torque [Nm] vs deflexion [deg]

the orientation of each link remains constant while the spring is stretched.

Thus, a leaf can be modelized as a flexible beam rigidly fixed at one extremity and submitted to a combination of a force F and a moment $M(F)$ with $M(F) = -a\,F/2$ such that a null inclination remains at the other extremity.

The material Young's modulus E is the slope of the corresponding curve on Figure 4 considering that the stretched spring is at temperature 20^oC (E varying from 1 to $20GPa$) while the contracted one is at temperature 120^oC ($E = 70GPa$).

The desired maximal flexion is 15^o. In this configuration, for $g = 0.135mm$, $e = 0.25mm$ and a number of leaves set to 6, we represent on Figure 6 the normalized output joint torque (the reference value is $0.01Nm$) and the normalized maximal stress in the material (the reference value is $135MPa$).

The best trade-off corresponds to $l = 2.35mm$ and $H = 2.0mm$ (i.e. $h = 0.125mm$). The output joint torque in this configuration is greater than $0.008Nm$ and maximal stress is less than $145MPa$.

5. Joint control

The distal end of the system is remotly driven. The endoscope configuration is self-guided in such a way that the local interactions between the instrument and its environment are minimized.

Changes in configuration are controlled at joint level by switching between position and a temperature control loops. The resulting controller for the antagonist actuators is represented on Figure 7. Only one spring is actuated at once for producing a displacement in the desired direction. When the error is large, position feedback is used (see below case 1 or 2). A switching on the temperature loop occurs when the static error is less than ϵ (see below case 3 or 4). The temperature input is the one memorized just before switching. If $\tilde{\theta}$

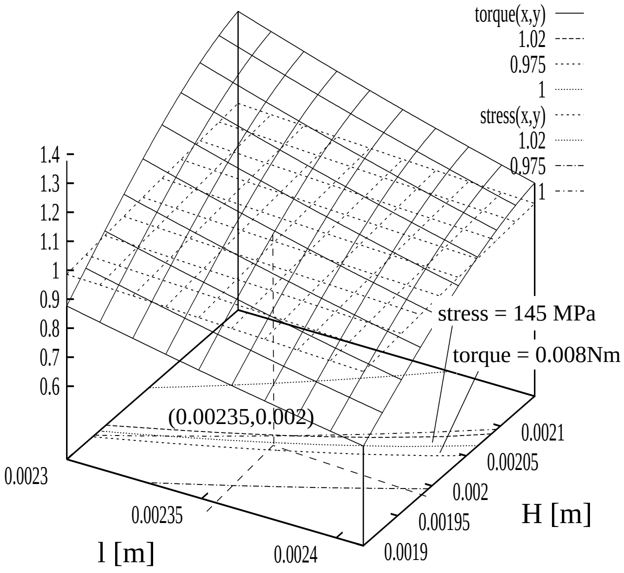


Figure 6. Normalized joint output torque and maximal internal stress for different SMA spring geometries

is the desired joint position and $\Delta\theta = \tilde{\theta} - \theta$ the joint position error, then the swiching rules are the following :

$$\begin{array}{l} \text{Case 1 : } \Delta\theta \geq 0 \ \& \ |\Delta\theta| \geq \epsilon \\ \text{Case 2 : } \Delta\theta \leq 0 \ \& \ |\Delta\theta| \geq \epsilon \\ \text{Case 3 : } \tilde{\theta} \geq 0 \ \& \ |\Delta\theta| \leq \epsilon \\ \text{Case 4 : } \tilde{\theta} \leq 0 \ \& \ |\Delta\theta| \leq \epsilon \end{array}$$

Figure 8 shows experimental results obtained in a position step response of a SMA actuator using this kind of switching controller. For the implementation of the local controller, we have developed a specialized micro-system based on hybrid electronic technologies. The temperature and position sensors which are electrical resistances, as well as the electrical connections are obtained by ink serigraphy on an alumina substrate. The power for SMA actuators and its electronics are transmitted by a two wires bus. The bending information is transmitted by modulation on the same bus.

6. Configuration behavior

Controlling the endoscope configuration aims at positionning and orienting correctly the tip of the structure while limiting forces coming from interactions with the environment.

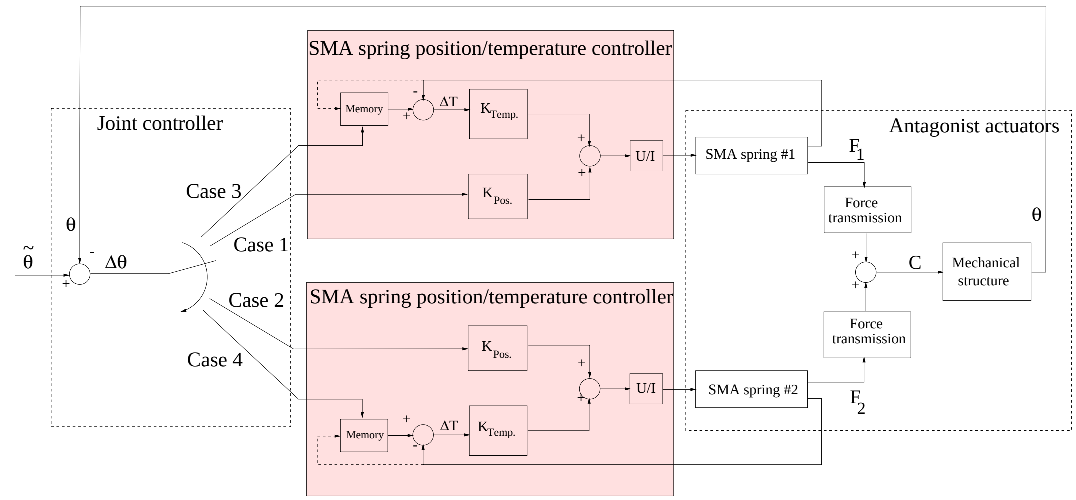


Figure 7. Joint position control

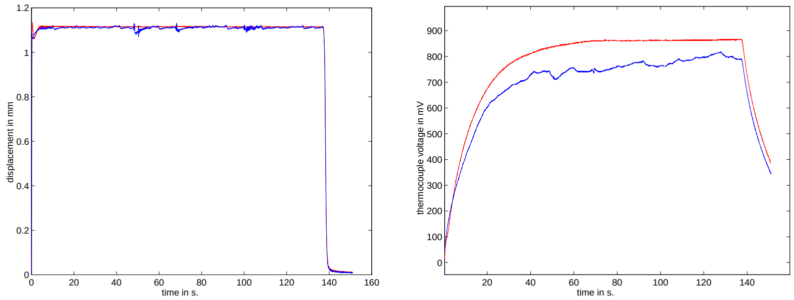


Figure 8. Step response with the position feedback controller (filled line) and the controllers combination (dotted line) (on the left-hand side) and the thermocouple output signal (on the right-hand side)

An algebraic resolution for this problem is extremely complex and the explored environment is a-priori unknown so a reactive resolution method is preferable.

The solution we propose relies on the virtual split of the steering mechanism into independent sub-systems and by considering them as agents [7]. Each agent is able to detect a contact with the environment and to accordantly modify the endoscope local configuration.

This is a very simple and modular solution indepedent from the length of the structure. Moreover, it is a strictly distributed approach minimizing the quantity of informations exchanged between the agents.

Three different kinds of local behaviors are described on Figure 9. They correspond to sub-systems composed of 1, 2 or 3 segments. The first behavior is very simple but it significantly disturbs the global configuration of the endoscope. The last one requiers information exchanges over three consecutive segments but preserve the global configuration.

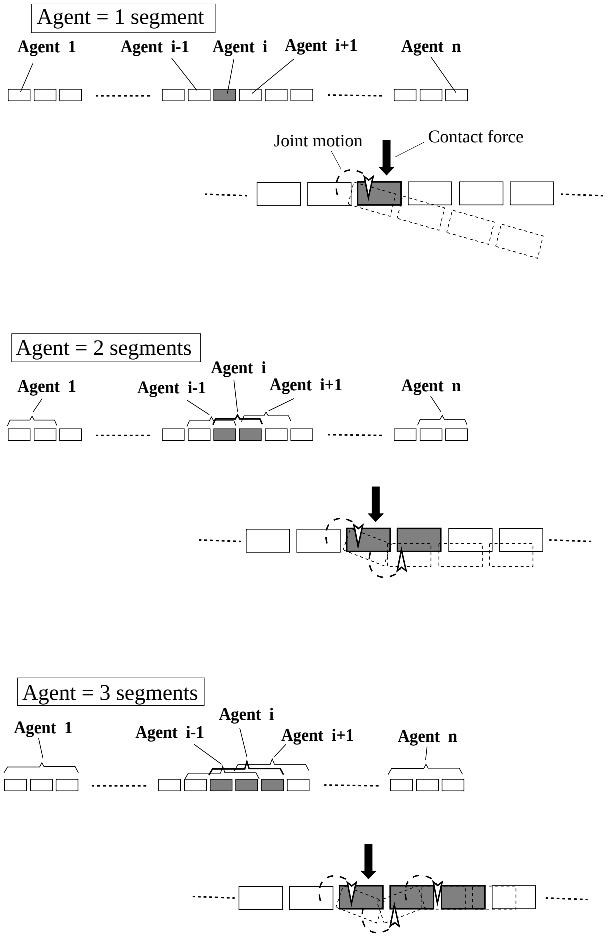


Figure 9. Three different kind of local behavior

The global behavior of a planar structure (20 segments) progressing into a pipe and guided by the local reaction of the agents only, has been tested in simulation. As shown on figure 10-b, ultra-local approch (agent $\equiv$ 1 segment), leads to instability. The second and third solutions (agent $\equiv$ 2 or 3 segments) keep the endoscope stable while minimizing interactions (Figures 10-c and 10-d).

7. Conclusion

This paper proposed a new design concept for actively guided steerable endoscope. At this point, the mechanical structure and the associated actuators have been manufactured.

The local controller has to be experimentaly improved and the whole integration has to be done for testing the proposed behavior control strategies.

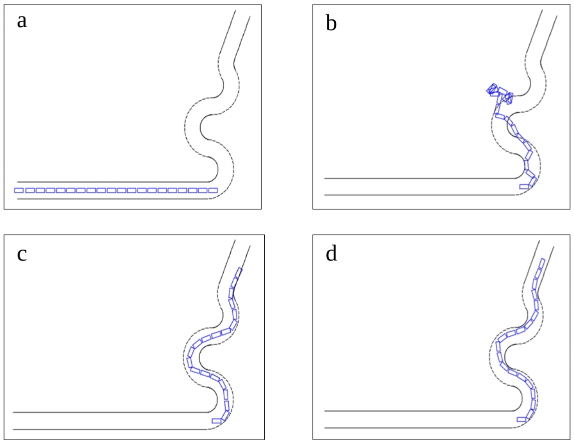


Figure 10. Multi-agent behavior simulation

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