Robotization of a ureteroscope for efficient semi-automatic vaporization of kidney stones

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I. Introduction

Kidney stones is a very frequent pathology. Estimations say that about 10% of people over 40 years of age in industrialized countries are affected, with a recurrence rate of 53% [1]. Among the techniques recommended by the European Association of Urology to treat this pathology [2], ureteroscopy allows the surgeon to treat stones of sizes up to 20 mm with a mini-invasive approach.

When the stone is larger than 4 mm it cannot pass the ureter and therefore must be treated inside the kidney. The operation process is the following: after introduction of the device into the kidney via natural ways, the surgeon navigates to find the stone and places it properly. A laser fiber is then introduced in the operating channel to eliminate the stone. A red light passes through the fiber to show the surgeon where the fiber points to. When the fiber points towards the stone, the surgeon pushes a pedal activating the power laser. The surgeon should ideally smoothly sweep the surface of the stone to vaporize it, but the the poor maneuverability of the device - it can only be bent on one plane from the outside - and backlash in the transmission mechanism make the operation uneasy. As a result, stones are often fragmented and brought to the outside one by one with a basket wire. Moreover, this operation is time consuming (about 1 hour to treat a stone of 1 cm diameter).

We propose to assist the surgeon in the vaporization task in order to reduce the operating time and avoid fragmentation of stones. The operation remains the same until the push on the laser pedal. At this stage our system handles the vaporization task automatically, under control of the surgeon: the next impact points of the laser appear on the video image, and the surgeon can stop the process if a laser shot is to be made outside the stone. This is allowed by the fact that the laser shooting rate is around 1 Hz.

The system we developed is depicted on Fig. 1. The actuation of the system relies on shape memory alloy (SMA) [3], [4]. The control of the system is made through a visual servoing scheme based on the ureteroscopic images. Those images are segmented to extract a safe region inside the stone which is used to plan a sweeping movement of the fiber.

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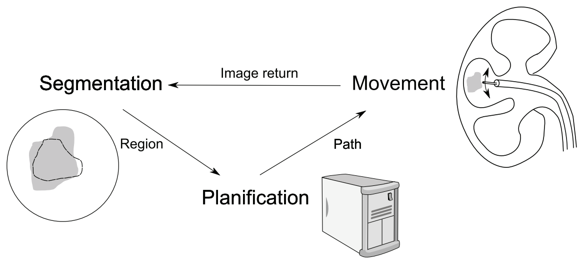

Fig. 1. The proposed command scheme

II. Actuation through SMA wires

A. Integration

Nickel-Titanium wires were used as actuators. This material has the property to change its cristallographic organization when heated, resulting in a shortening of the wire of 4 to 8% of its total length. Hence, wires integrated to the distal tip of a catheter can bend it, as showed on Fig. 2.

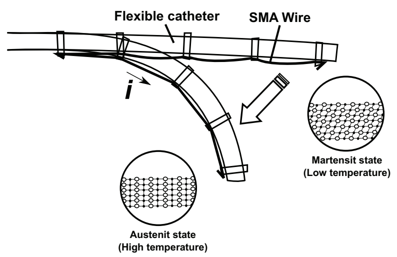

Fig. 2. Bending of a catheter using the shape memory effect of a SMA wire.

Using this principle, three SMA wires were mounted at 120 degrees on the distal tip of a ureteroscope as showed on Fig. 3. They were attached at their two extremities and passed inside two bushings to allow translation of the wire while keeping it close to the ureteroscope. Their length was calculated to reach the limits of a 20mm wide stone with the ureteroscope at 1 cm distance from the stone. A security factor of 2 was chosen, which led to wires of 2.5 cm length. 175 μm diameter wires were used. The outer diameter of the prototype was 4 mm, which is the inner diameter of the ureteral shteaths commmonly used for ureteroscopy.

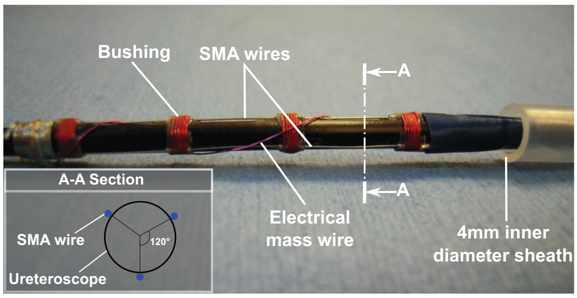

Fig. 3. Integration of the SMA wires to the distal tip of the ureteroscope

B. Validation

A validation was made at the urology department of Pitié-Salpétrière Hospital (Fig. 4). The prototype was found to be effective to reach the extreme points of a 13 mm kidney stone. Comparisons between actuation by the urologist and actuation using the SMA wires resulted in a much smoother movement of the tip of the ureteroscope in the second case.

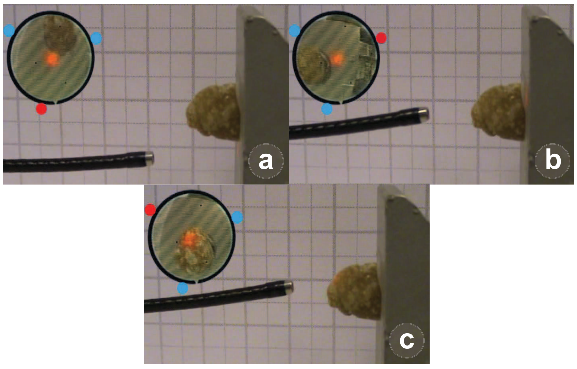

Fig. 4. Validation of the limits of the mechanical system. The upper left view is the endoscopic view, the blue points are the cold SMA wires and the red point is the hot SMA wire. a: movement down. b: movement right. c: movement left

III. Command

To command a smooth sweeping of the surface of the stone, a careful planning of the movements of the ureteroscope tip is needed. For that, we implemented an image based control of the SMA actuators. It relies on an efficient stone edge detection algorithm.

A. Segmentation of the ureteroscopic images

The segmentation of ureteroscopic images is very difficult. First of all, kidney stones come in different chemical compositions, resulting in different shapes, colours, and textures [5]. Moreover, the fiber bundle of the ureteroscope is also fragile, and black dots frequently appear on the image. An algorithm was developed taking these constraint into accounts. It was kept very simple because of the fact that this particular problem was never handled in the past.

A region growing algorithm was used. The algorithm starts as the surgeon pushes the laser pedal. The fiber then points towards the stone. A detection of the red spot gives the starting point for the region growth. The algorithm parameters tuning and validation were made on a dataset composed of 903 images coming from 10 videos presenting 4 different compositions of stones with sizes varying from 9 to 19 mm. The images were manually segmented by an exepert to serve as ground truth, using common performance indicators such as F-score, compactness, and Yasnoff measure. The algorithm parameters were tuned to obtain good results on different kinds of kidney stones. The algorithm has a computational time which allows to run it at a video framerate of 25 frames/s. An example of segmented image is shown on Fig. 5.

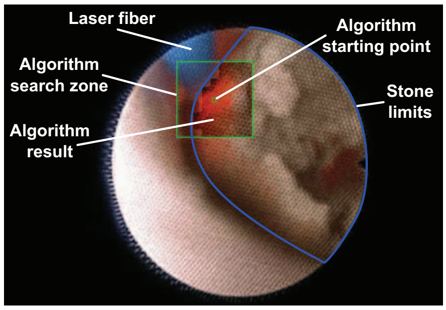

Fig. 5. Example of segmentation obtained with the developed algorithm

B. Visual servoing

A visual servoing scheme was developed. It doesn't rely on any formal relation between the heating current and the shortening of an SMA wire. Equations linking the temperature to the shortening of the wire exist, but our system doesn't embed a temperature sensor. Therefore, the relation between the electrical current in input and the resulting movement has been determined experimentally, and has been integrated in the control scheme.The movement of the ureteroscope results from a vectorial composition of the movements produced by the SMA wires individually (Fig. 6). The regulation was made through a simple PD regulator. A simple testing was developed in which the ureteroscope was actuated to bring a designated point at the center of its image. The system was able to carry out any displacement in its field of view with good accuracy.

C. System bandwidth

The algorithm frequency is greater than 30 Hz and the video is acquired at 25 Hz. Hence, the system bandwidth is mainly limited by the dynamic of the SMA wires. The heating and cooling times of the SMA wires were found to be 0.4s and 1.0 s respectively. However, the proposed control scheme aims at limiting the influence of the cooling time as

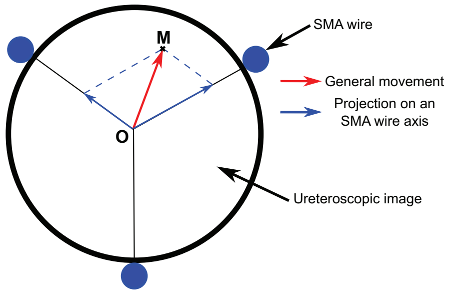

Fig. 6. Composition of movements to reach the point M on the ureteroscopic image

it never lets the system evolving under the sole effect of the natural convection. Exploiting the antagonistic positionning of the SMA wires (Fig. 3), it always maintains the system under the control of one active SMA wire at least, whatever the commanded displacement is. Additionaly, a cooling water can be used by the surgeon during the ureteroscopy in order to facilitate the cooling of the wires. Hence, the system bandwidth can be considered to be more than 2.5 Hz, which is sufficient, compared to the laser shooting rate of 0.8 Hz.

IV. Conclusion and future work

An SMA based active ureteroscope prototype was proposed to solve the problem of effective vaporization of kidney stones. An algorithm for kidney stones segmentation based on ureteroscopic images was developed and tuned for a general use. The system was successfully commanded using visual servoing.

The integration of a path planning with the command of the ureteroscope distal tip movement through visual servoing is the last step towards a complete operating prototype.

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