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Conceptual Design of a Miniaturized Hybrid Local Actuator for Minimally Invasive Robotic Surgery (MIRS) Instruments

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Abstract— **The actuation mechanism of the tip of an endoscopic instrument is a major problem in designing miniature scale motorized instruments, especially when a high level of functionality and multi degrees of freedom (DOF) are concerned. We evaluated the different possible actuation methods for an endoscopic needle holder and proposed a new design of hybrid local-actuation, including a micro DC motor and a piezoelectric (PZT) actuator. The DC motor provided the long movement course required for opening-closing function of the gripper while the PZT guaranteed the high gripping force required for holding the needle. A compact serial configuration was considered for the actuators, producing an overall size of 10 mm in diameter and 39 mm in length, so that it could be implemented in the limited space available. The efficacy of the design was analyzed in a simulation study, using FEM and it was shown that the needle holder is capable to apply a sufficiently high gripping force of 22 N.**

I. INTRODUCTION

Minimally Invasive Robotic Surgery (MIRS) is the practice of performing surgery through small incisions using specialized surgical instruments and Master- Slave robots [1, 2]. Several actuation methods have been proposed for the MIRS instruments in the literature. Canfield et al. [3] developed a single degree of freedom actuation mechanism using smart materials. Cappelleri, et al. [4] designed a piezoelectric bimorph actuator for MIS instruments. Morra et al. [5] examined the performance of a set of parallel SMA (Shape Memory Alloys) wires to open a gripper while closing function was provided by a spring. Salle et al. [6] evaluated a variety of surgical grippers actuated by electromotor and SMA. Deok-Ho et al. [7] analyzed a superelastic alloy (NiTi) micro gripper with integrated electromagnetic actuators and piezoelectric force sensors. Kode et al. [8] proposed a hybrid actuator consisted of a micro DC motor to open and close the gripper jaws and a SMA actuator for holding the needle. Tholey et al. [9] developed a compact and modular laparoscopic instrument including a DC motor with incremental encoder, a linear positioning assembly, and a quick-connect mechanism to attach/detach the modular tool.

Design and development of instruments with smaller diameter and more degrees of freedom is an essential need to improve the MIRS. The present study deals with the design of an effective actuation mechanism for an endoscopic needle holder. We evaluated the different possible solutions in detail and proposed a local hybrid actuation mechanism, consisting of a micro DC motor and a piezoelectric actuator in a serial configuration.

II. DESIGN REQUIREMENTS

In order to select the most appropriate actuation mechanism for an endoscopic needle holder, several design parameters should be considered. In particular, the overall diameter of the actuation system should be small enough (under 15mm diameter) to pass through the standard surgical trocars. Also, the actuating mechanism should be able to provide a sufficiently large gripping force at the jaws, in the range of 16 N [9] to 40 N [6, 11]. Some other design parameters include the stroke length, response time, working cycle, controllability, and compatibility with operation room [10].

Considering the above range of actuating force at the jaws of the needle holder, a detail force analysis is required to find the force that should be provided by the actuation mechanism,. Most of the commonly used needle holders consist of a fixed and a moving jaw. The fixed jaw is a part of the main frame and the moving jaw is a link of a 1 DOF mechanism which is closed on the fixed jaw by rotating around a hinge. The moving jaw is connected to a thin rod through another pin. Closing function of the needle holder jaws is obtained by pulling or pushing the thin rod, depending on the design. The schematic mechanism of a needle driver is shown in figure 1.

The diameter of a surgery needle is about 0.01 mm up to 0.8 mm depending on different suturing tasks. Also in a typical needle holder [12] a, c and α in figure 1 are 0.7mm, 5.3mm and 10°, respectively. Assuming a maximum gripping force of 40N at the jaws, the actuating force, F, could be obtained using the moment equilibrium condition:

$$\sum M = 0 \quad (1)$$

$$(F sin\alpha \times c) + (F cos\alpha \times a) = 40 \times b \quad (2)$$

So, assuming a typical position of b= 10mm for the needle (Fig 1), the maximum actuating force required at the gripper's rod would be 250N.

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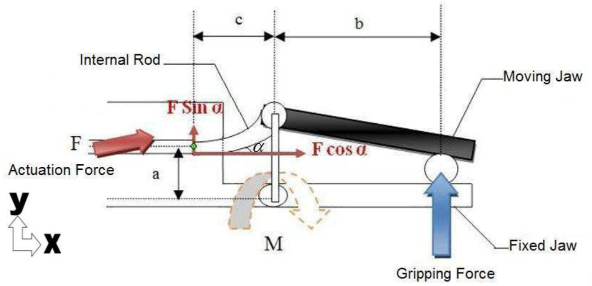

Fig.1. Schematics of the closing-opening mechanism of the jaws of a needle holder: a, c, d and α are constant design parameters and b is a variable depending upon the needle's position.

III. DESIGN OF ACTUATION SYSTEM

The performance features of a wide variety of actuation methods were evaluated using the literature. For actuation of a needle holder, there are two approaches that seem to be most appropriate: (1) a micro DC motors, and (2) a hybrid actuator consisting of a smart material and a micro motor.

At first the actuating approach based on a single micro DC motor was considered. In this design, the angular motion of the motor shaft is to be converted to a linear motion to push/pull the gripper rod. This task can be performed using a nut-screw mechanism. To simplify the design, one can thread the internal rod of the gripper to be used as the screw. Considering the diameter of the holder rod is about 1.7mm, we designed the thread pitch to be compatible with a regular M2 screw with a pitch of 0.4mm. However, due the fact that the conventional power screws, such as ball and square thread screws, are not available in this size we used a regular triangle thread design with a thread angle of 60°. The force-torque relation of such screw is obtained from the following [13]:

$$T = \frac{F d_m}{2}\left(\frac{l+\pi\mu d_m \sec\alpha}{\pi d_m - \mu l \sec\alpha}\right) \qquad (3)$$

Where dm, l, and α are the mean diameter, the pitch and the half of the thread angle of the screw, and μ represents the friction constant which is considered to be 0.3. Replacing the designed parameters in Eq. (3), would results in a torque of about 0.07 Nm.

Now, for the needle holder, assuming a rod stroke of about 2.5mm, and an actuating time of 0.5s, the velocity of linear motion would be about of 5 mm/s. So, considering the 0.4mm thread pitch, the required output speed of the motor would be obtained to be 750 rpm. Among the micro DC motors available within the size range of 10 to 15mm, we first considered the 4.5W, 16mm Maxon DC motor [17] with 44900 rpm nominal speed. So, a gearhead reduction ratio of 60:1 is required for this motor. From the information available in the catalog, using such a motor and gearhead would lead to a length of more than 80mm which is not feasible.

Other options for the micro DC motor were also evaluated. To obtain an overall length of motor-gearhead assembly of less than 50mm, the powerful 8W, 10mm diameter Maxon DC motor with a nominal speed of 6500rpm was also considered. This motor needs a reduction ratio of 8.66 while the nearest available gearhead ratio is 4:1 with a 0.01Nm output torque for the motor-gearhead assembly. Obviously, this torque could only provide a 23.8N force in the holder rod and thus 2.5N gripping force at the needle.

In the next stage, the feasibility of the second actuating approach, based on a hybrid smart material- DC motor actuation system was investigated. The main idea behind was a hybrid design which combines the advantages of the DC motors and the PZTs. Such combination can employ the positive attributes of both PZT and DC Motor and eliminate their drawbacks. In the proposed design, a mini DC Motor and a PZT actuator are configured in a serial combination (Fig 2), to perform the actuation task in a double- phase procedure. At the first phase, the miniature DC motor provides the large displacement needed to close the jaws. Then, at the second phase, the piezoelectric actuator acts as a linear actuator to ensure that the needle is hold firmly by the jaws. So, the role of the PZT actuator would be just to provide the final gripping force and it is not involved in opening - closing motions of the gripper.

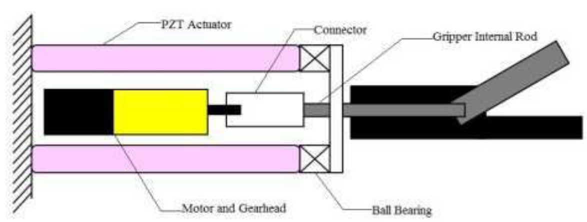

Fig. 2. Schematics of the designed hybrid actuation system, including a DC motor and a PZT actuator configured serially.

A more detail description of the function of the hybrid actuator is as the following. At first, the DC motor rotates clockwise to move the needle driver jaws from the open configuration to the close configuration. As the jaws reached the close configuration, the DC motor is stopped and the PZT is actuated by applying a proper voltage. Actuation of the PZT leads to its instant expansion, pushing the motor and other parts, including the needle driver's internal rod, forward. Although the expansion of PZT is only in a range of microns but as the DC motor has already frustrated all backlashes, even such a small expansion causes a large force at the rod of the needle holder which is subsequently transferred to the jaws. In order to open the needle driver jaws, on the other hand, at first the PZT actuator is switched off. So, the force on the gripper jaws is removed quickly and the motor and other parts of the system would be free to go back to their initial position, thanks to the fast response of the PZT. Finally, with the counterclockwise rotation of the motor, a pull force is applied to the rod of the needle holder to opens the jaws.

IV. DESIGN OF ACTUATED NEEDLE HOLDER

The designed actuation mechanism was considered to be adapted on a DUFNER 4.5mm endoscopic needle holder. A 4mm diameter Namiki DC motor [14] was selected to carry out the first phase of the actuation procedure. The micro DC motor and gearhead are connected to the internal rod of the needle holder in order to push/pull it into close/open configurations of the jaws. To accomplish this task, the motor shaft is connected to a connecter, threaded inside, which holds the motor's shaft firmly (Fig 3). This connector consists of two parts, i.e., the head and the body. The head is screwed on the body and keep the motor shaft inside the connector. The hole at the body plays the role of a nut so that the gripper's threaded rod is able to go back and forward inside the hole due to rotations of the motor's shaft.

During assembly, at first the body of the connector is assembled on the shaft and then the head is screwed on it. This would provide a firm and reliable attachment to the shaft due to the closure of the body's longitudinal threads when the head is screwed. To prevent the body of motor from rotation, a holder is driven through it to be fixed by set screws to the main frame. On the other hand to assemble the needle holder and actuation system, the 1.7mm internal rod of the needle holder is threaded outside. The schematic assembly of the designed actuator, including the connector, motor holder, motor and gearhead are shown in figure 3.

During first phase of operation, when the motor's shaft rotates, it drives the connector and so the gripper's rod to move forward/backward and provide the closing/opening motions.

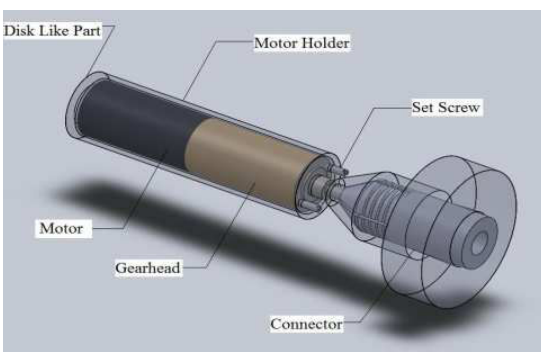

Fig. 3. The schematic assembly of the designed actuator, including the connector, motor holder, and motor and gearhead.

To perform the second phase of the actuation procedure, the PZT must be placed in a serial arrangement with the DC motor. The design should be in such a way that PZT actuator pushes the inner rod to provide the required gripping force. The main problem in adding the PZT to the system is that the design must be in such a way that no axial load is applied to the shaft of micro motor. Of course, the first idea is placing the PZT in the back of the DC Motor. However, this design will increase the length of the actuation system. To avoid this, a hollow PZT actuator was chosen to locate the micro motor inside it. In order to prevent the transfer of PZT axial load to the shaft of the micro motor, a thrust ball bearing is fixed to the PZT. Considering the fact that the motor must be able to move inside the hollow PZT, the inner hole of the PZT is considered to be at least 5mm. When the motor starts working, it drives the connector and by pushing the rod closes the moving jaw till it reaches the suture needle. At this point the connector's head pushes the ball bearing, to prevent backlashes, and the motor stops.

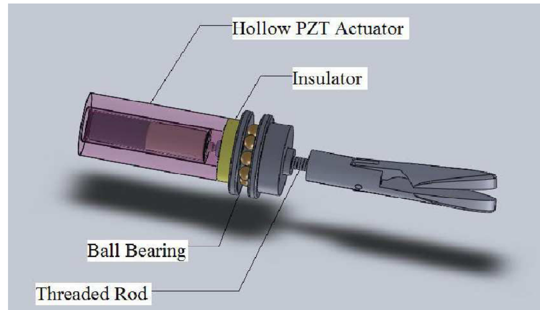

Fig. 4. Schematic assembly of the hollow PZT actuator and needle holder.

The next phase of the actuation procedure starts with applying proper voltage to PZT. The resulting expansion of PZT pushes the connector and eventually the gripper's rod forward. So that, the jaws of the gripper are forced to hold the needle firmly with a sufficiently high gripping force.

V. Simulation and Analysis

Although PZT actuators can apply high forces against rigid objects, their ability for force application drops considerable when the object can be deformed. Reference [15] suggest following relations to calculate the effective force of hollow PZT actuators:

$$\Delta L \approx \Delta L_0 . \left(1 - \frac{K_T}{K_T + K_S}\right) \quad (4)$$

$$F_{max,eff} = K_T \times \Delta L \quad (5)$$

where L_0 and K_t, are the nominal displacement and stiffness of piezoelectric actuator, K_S is the stiffness of external object, and $F_{max,eff}$ represents the maximum effective force that the actuator can generate.

In this study, we considered the actuators available by PI Company [16]. According to the design configuration and considering the limitations for internal diameter, external diameter and length, a hollow PZT actuator with nominal displacement of about 30μm, and the stiffness of about 59N/μm was selected. To calculate the PZT effective force, the external stiffness, or the overall stiffness of the needle holder, was needed. Considering the preload provided by the motor, the backlashes of joints were neglected and a finite element analysis was performed to find the force-deformation behavior of the needle holder. The Geometrical data was based on DUFNER needle driver [12]. The fixed jaw of the needle holder was considered as the base and other parts were connected to it or each other using contact elements. Figure 4 shows the result of FEM analysis which was performed using ABAQUS/CAE (SIMULIA) software. The results indicated that the rod moved about 50μm under 250N force, suggesting a stiffness of 5 N/micrometer for the external object which results in a 22N gripping force.

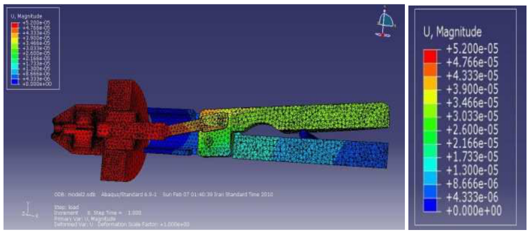

Fig. 5. Displacement field of the needle holder

VI. CONCLUSION

A hybrid design consisting of a micro DC motor and a PZT actuator is proposed to enjoy the large range of motion of DC motors and high acting force of PZT actuators. In the proposed hybrid system, although the motor and the PZT are in parallel geometrically, they are configured to act in serial mechanically. The micro DC motor accomplishes the opening-closing phase of the actuation procedure with a high speed while the PZT actuator performs the second phase by supplying the gripping force. The PZT actuator is of hollow stack type which encloses the motor; hence, resulting a sufficiently compact design. The system is approximately 39mm in length and 10mm in diameter. Results show that the actuator is able to perform 138N actuating force which causes about 22N gripping force on the needle. This force is the range of 16 to 40 N gripping force recommended in the literature.

In general, the local-hybrid type actuation system designed in this study is much more powerful in comparison with simple DC *motor* actuators and meets the design requirement well. However, there are several challenges in order to achieve an acceptable performance in practice. The PZT actuator has to be firmly fixed from at the ends to avoid micro motions. The parts of the system need to be manufactured and assembled with minimum backlash. Also, the motor should be constrained from rotating backward when the PZT is actuating. Further work is going on to fabricate a full functional prototype of the instrument for technical and application tests.

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