Surgical Robotic Manipulator Based on Local Magnetic Actuation[1]

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1 Background

Magnetic coupling is a strategy to transmit actuation forces across a physical barrier. This approach can be applied to remotely control and manipulate robotic instruments in minimally invasive surgery (MIS) [1]. Interrupting the mechanical continuity of such system by having surgical instruments and laparoscopic camera magnetically coupled across the abdominal wall greatly enhances both the workspace of operation and triangulation without the need for multiple abdominal incisions [2]. On the other hand, continuum robots are able to provide a large amount of mechanical power to accomplish surgical tasks [3]. Focusing on the typical surgical task of suturing a tissue, 1 N of force in any direction and 180 deg per second rotational speed must be achieved throughout a $50 \times 50 \times 50$ mm^3 workspace [3].

In Ref. [4], the authors introduced the concept of local magnetic actuation (LMA), where mechanical power is transmitted across the patient abdomen by specific magnetic couplings to drive the degrees of freedom (DOF) of the robotic surgical instrument. This approach removes the need for electromagnetic motors on board and wired connections.

The LMA-based surgical retractor presented in Ref. [5] combines two pairs of magnets, one providing anchoring and the other transferring motion to the internal mechanism actuating a single DOF. This study shows the feasibility for the LMA approach to transfer a relevant amount of mechanical power to produce forces of up to 5 N.

Previous papers, such as Ref. [6], have proposed the use of cable-driven mechanism in surgical applications. Major advantages of cable-actuation are the light weight, small size, transmission of force to hard-to-reach location, and high bending radii.

The design presented in this paper aims to develop a surgical manipulator for MIS able to perform surgical tasks combining mechanical power transmission based on LMA and cable-driven actuation of a novel design of spherical parallel wrist.

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2 Methods

This robotic manipulator features an LMA-actuated 4DOF cable-driven spherical wrist, which is schematically represented in Fig. 1(*a*) and referred to as multiDOF–LMA. The final prototype has a diameter less than 15 mm allowing it to enter from a standard 15-mm trocar for MIS. The multiDOF–LMA design has three actuation units (AcU) and an anchoring unit (AnU). Each AcU provides the mechanical power to actuate 1DOF of the wrist through a pair of antagonistic cable drive. The AnU provides for the gross positioning, support, and through its ability to translate, also provides the actuation of the tilt angle (θ_1) DOF of the multiDOF–LMA.

The AcU consists of a couple of diametrically magnetized magnets—the external driving magnet (EDM) and the internal driven magnet (IDM)—designed to transmit mechanical power from the external motor to the mechanism embedded inside each of the transmission modules (TM) 1–3. The gear transmission inside the TM amplifies the torque delivered by the IDM to the antagonistic-cables attachment. Each TM is equipped with a planetary gear train (1:16 gear ratio), a set of spur gears (1:14 gear ratio), and a cable reel (2.5 mm radius). The two antagonistic-cables lines are connected with the reel and rolled-up by lengths S_1, S_2, and S_3, respectively, for each actuated DOF of the spherical wrist. Each TM is magnetically anchored against the abdominal wall by magnetic coupling with the correspondent EDM; also, each TM is connected to the manipulator's link 1 through flexible pipes hosting the pair of antagonistic cables.

The AnU consists of a pair of axial magnetized permanent magnets. The external anchoring magnets (EAMs) are connected to each other by motorized linear slide. The EAMs are magnetically coupled with the internal anchoring magnets generating the forces to support the multiDOF–LMA during operation by offering two points of contact with the abdominal wall. For a typical abdominal surgery procedure, we considered a toroidal workspace with a height of 30 mm and a diameter of 60 mm located 10–15 cm below the insufflated abdominal wall. The AnU also provides the actuation of joint 1 (J_1) to orient the manipulator tip along the direction of interest.

The multiDOF–LMA design has a novel configuration for a 3DOF cable-driven parallel wrist with no kinematic singularity in the joint limited workspace and decoupled cables actuation. The spherical wrist, showed in Fig. 1(*b*), features a simple design with a parallel configuration. It is composed of a U-joint followed by a helical actuated serial joint [7]. The U-joint provides the parallel actuation of the tip along the axes $\mathbf{x}_0$ and $\mathbf{y}_0$ in a range of ± 60 deg with respect to the wrist frame coordinate system. The ends of the two pairs of antagonistic cables are connected to the U-joint output link (UOL) and spaced by 90 deg to each other. The helical actuated joint is composed of two cylindrical links, H_1 and H_2, one on top of the other, where H_1 can freely rotate relative to H_2. The helically actuated joint is mounted on top of the UOL and provides the tip rotation about $\mathbf{z}_2$ of the UOL coordinate system. The antagonistic cables are connected on the outer side of H_1 and helically rolled around H_1 and H_2, one clockwise and the other counterclockwise. This cable arrangement allows for a rotation of ± 180 deg around $\mathbf{z}_2$ in either direction, depending on the cable that is remotely pulled.

On the tip of the manipulator, a cable-driven endoscopy flexible grasper could be attached to achieve the desired surgical tasks. The flexible grasper is inserted through the single abdominal access; it enters from the posterior of the multiDOF–LMA and exits from the tip of the manipulator. The flexible grasper could be externally actuated to generate up to 40 N grasping forces [3].

3 Results

A prototype implementing the design described above has been fabricated and preliminary tested, qualitatively confirming the functionality of the novel cable-driven spherical wrist (Fig. 1(*c*)).The permanent magnets implementing both AcUs and

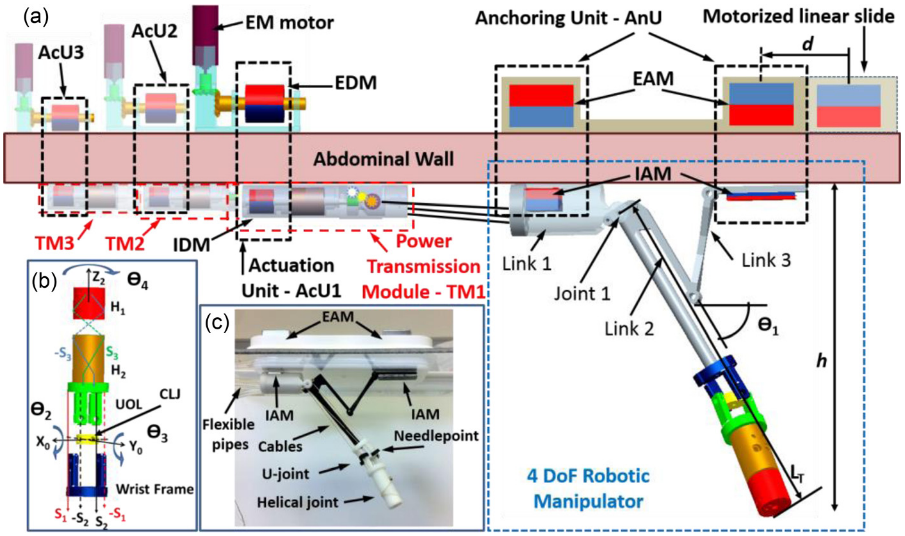

Fig. 1 (*a*) **Schematic view of the multiDOF–LMA design, (*b*) the spherical wrist schematic design, and (*c*) the prototype implementation picture**

AnUs have been tested and reported in Ref. [5]. Typical attraction forces are within the range of 1–5 N, and actuating torque within 2 mNm to 8 mNm, considering a distance between the external and internal magnets below 6 cm.

The tilt angle θ_1 about J_1 achieved by the relative motion d between the EAMs is defined as following: $\theta_1 = \cos^{-1}[(L-d)/(2l)]$, where L is the initial distance between the EAMs, and l is the length of both links 2 and 3. L_T is the whole length of the multiDOF–LMA from J_1 to the tip. If the EAM is moved by d, the robotic tip reaches the distance h from the abdominal wall, such as: $h = L_T \sin\{\cos^{-1}[(L-d)/(2l)]\}$.

The two pairs of antagonistic cables connected at the U-joint actuate the angles θ_2 and θ_3, as shown in Fig. 1(*b*). Each cable goes down along the U-joint structure passing through a needlepoint at the cross link junction (CLJ). This cable constraint provides an even cable length variation during the U-joint actuation, thus decoupling the cables. The kinematic equation relating the antagonist cable displacements S_1, S_2, and the angles θ_2 and θ_3 is $\Delta S_{1,2} = l_u - (l_u^2 + r_u^2)^{1/2}\cos(\tan^{-1}(r_u/l_u) + \theta_{2,3})$, where l_u is the UOL length and r_u is the UOL radius.

The antagonistic cables actuating the helical joint are connected on the outer side of H_1, controlling the rotational angle θ_4. The cables follow a helical path along the outer cylindrical surface of radius r and pitch $2\pi l_h$, where r is the helical joint radius and l_h is the length of both H_1 and H_2. The following parametric function describes the cable trajectory helically rolled along H_1 and H_2: $t \rightarrow [r\cos(t),\ r\sin(t),\ l_h\, t/(2\pi)]$, where $t \in [0, 2\pi]$. In order to achieve $\theta_4 = \pm 180$ deg, the cable displacement S_3 is actuated as follows: $\Delta S_3 = l_h/\pi\theta_4$. The cable decoupling is achieved by pushing the cable pair through the CLJ center hole. The estimated transmitted force at the tool tip, considering a 2 mNm available torque at each AcU and a 50% of efficiency, is about 16 N for each direction of motion. The maximum estimated speed at the tool tip, considering the IDM rotating at 10,000 rpm, is 58 deg/s, thus it covers the entire workspace for the U-joint in 2 s.

4 Interpretation

Thanks to the LMA actuation strategy and to the presented cable-driven mechanism, battery and motors are located externally, resulting in a manipulator with significant torque/speed performance. The novel spherical wrist design is antagonistically cable-driven, has no kinematic singularity, and presents cable decoupling. The proposed design paves the way for disposable low-cost implementation of robotic laparoscopic surgery.

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