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CYCLOPS: A Versatile Robotic Tool for Bimanual Single-Access and Natural-Orifice Endoscopic Surgery

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***Abstract*—This paper introduces the CYCLOPS, a novel robotic tool for single-access and natural-orifice endoscopic surgery. Based on the concept of tendon-driven parallel robots, this highly original design gives the system some of its unique capabilities. Just to name a few, unparalleled force exertion capabilities of up to 65N, large and adjustable workspace, bimanual instrument triangulation. Due to the simplicity and nature of the design, the system could be adapted to an existing laparoscope or flexible endoscope. This promises a more immediate and accelerated route to clinical translation not only through endearing low-cost and adaptive features, but also by directly addressing several major barriers of existing designs.**

I. INTRODUCTION

Surgical innovators are currently pursuing a second renaissance in minimally invasive surgery (MIS) techniques. The first-generation of MIS was defined by a paradigm shift from traditional large open surgical incisions to multiple small ‘key-hole’ incisions. This transition inferred many patient benefits, contributing to the acceptance of MIS as standard surgical care in many settings. Today, there is growing momentum towards further minimizing access trauma such that many procedures may be essentially ‘scarless’ when performed via single-incision laparoscopic surgery (SILS), natural orifice endoluminal surgery (NOES) and natural orifice transluminal endoscopic surgery (NOTES) techniques.

While it seems logical and naturally progressive to refine, or re-define, surgical techniques to be more minimally invasive, the reality of these ambitions is that they are inextricably reliant upon enabling technology. Potentially disruptive novel techniques need tools that are purpose designed to fulfill these clinical needs. Such gateway technology inevitably involves fundamentally bespoke features, ranging from entirely unique platform design to radical modification of existing market items. With the exception of improved image quality and minor adjustments in scalability, the laparoscope and flexible endoscope are items of surgical technology that remain essentially undisturbed since they were first introduced several decades ago and still are the default platforms for SILS, NOES and NOTES. It is unsurprising therefore, that several novel techniques have achieved little progression beyond the experimental phase, despite nearly 10 years of committed effort. There are currently a variety of prototype platforms for SILS, NOES and NOTES that are being developed worldwide by a number of academic groups. Most platforms remain in the pre-clinical phase with only a small number having reported feasibility in in-vivo settings. The most notable ones are discussed by Vitiello et al in [1] and are shown here in Fig. 1. Major limitations of these prototypes are universally shared. These pertain to adequate triangulation, force delivery, stability and control.

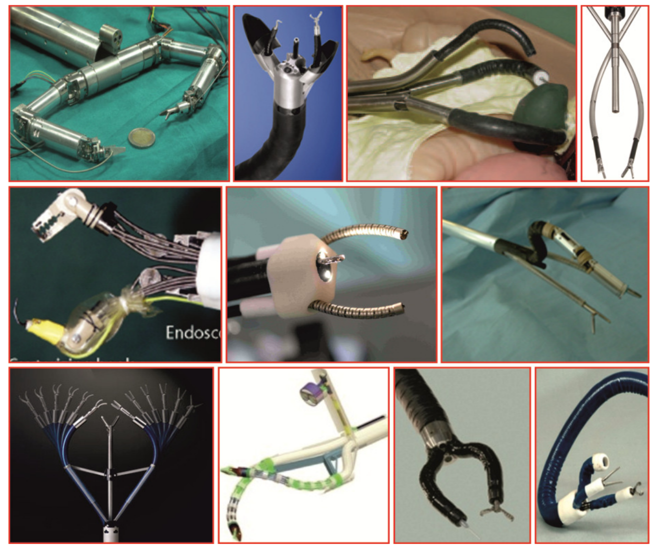

Fig. 1. A selection of current prototype and commercial platforms for SILS, NOES and NOTES from [1]. *First row:* SPRINT (Scuola Superiore Sant-Anna), Anubiscope® (Karl Storz), HVSPS (TUM), Single-Port (Intuitive Surgical). *Second row:* MASTER (Nanyang Technological University), Master-Slave (Strasbourg/IRCAD), i-Snake® (Imperial College London). *Third row:* SPIDER® (TransEnterix), IREP (Vanderbilt University), EndoSamurai™ (Olympus), Cobra™ (USGI Medical).

The CYCLOPS design seeks to overcome the above limitations by addressing bimanual instrument triangulation and force-delivery over a large workspace via a highly original design which is based on the concept of tendon-driven parallel robots. The system is adaptive to the existing laparoscope or flexible endoscope, while the stability and the navigational control of these existing instruments are preserved. This paper is dedicated to the description of the CYCLOPS concept, its current stage of development and supporting preliminary data. To the authors’ knowledge, this is the first design of its kind, demonstrating functional capabilities unmatched by existing platforms.

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Patent application **GB1316333.2** has been filed for the presented system.

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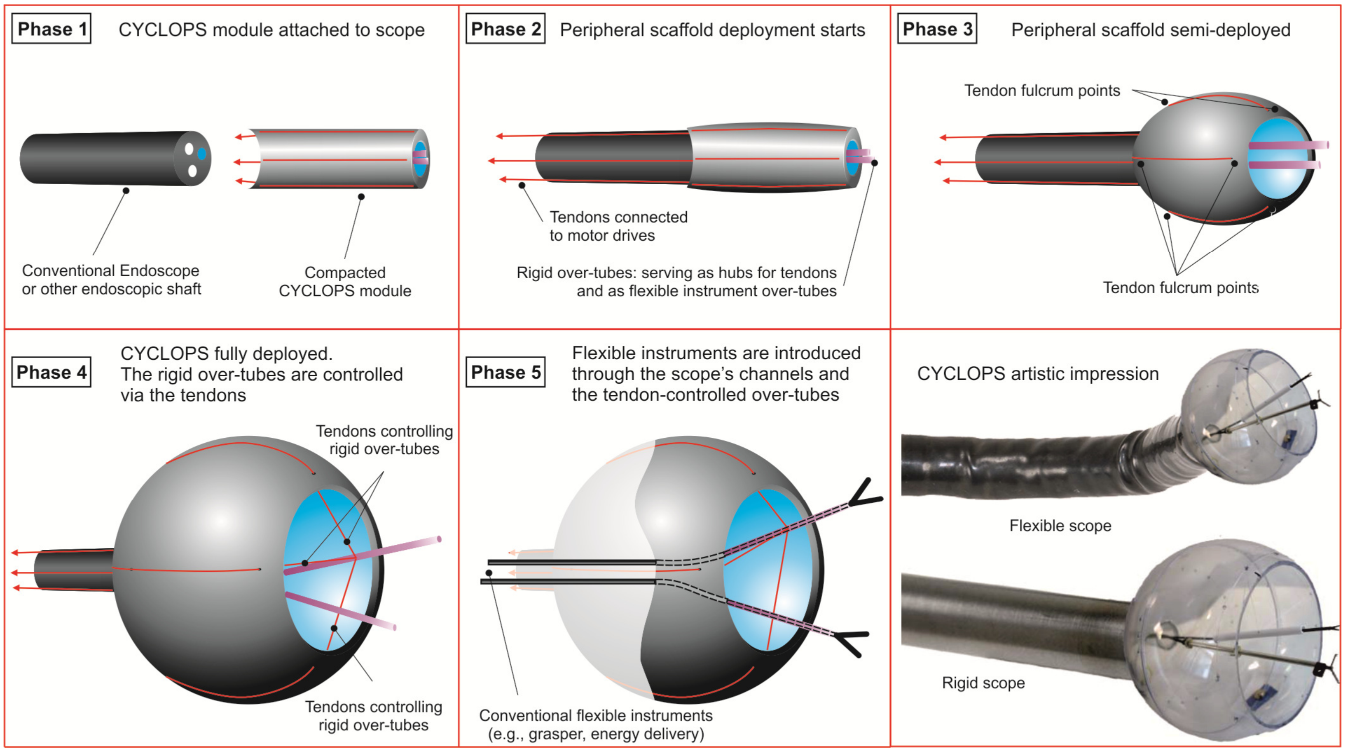

Fig. 2. The conceptual design of the system showing the CYCLOPS module attached to a standard endoscope, the peripheral scaffold deployment phases, the tendons controlling rigid over-tubes, and the introduced flexible instruments, followed by an artistic impression of the envisaged system as a clip-on adaptor to conventional scopes.

II. System Description

In this section, the *conceptual design* of the CYCLOPS is introduced first, followed by a detailed description of its core component -the *tendon-driven parallel robotic manipulator*. Lastly, a description of the first *working prototype* of the CYCLOPS system is provided.

A. CYCLOPS Conceptual Design

With reference to Fig. 2, the unique component of the CYCLOPS is a deployable peripheral structure resembling an open-ended bulb, attached at the distal end of an endoscopic shaft. Ultimately, it can be adapted and fitted at the distal end of a conventional laparoscope or flexible endoscope (henceforth both referred to as "scope"). The peripheral structure is low profile and un-obtrusive to the functionality of the main scope as it maneuvers to the target anatomy. In its collapsed state it can be integrated by means of a scope over-sheath or pre-affixed cap attachment. Once appropriately located at the operative site, the structure is deployed in a gradual and controlled manner to form an expanded near-rigid scaffold that is covered with a soft sheet-like biocompatible material. Its size can be scalable to suit procedural needs. A network of tendons is arranged within the bulb to actuate rigid hollow over-tubes which can then be controlled in adequate degrees-of-freedom (DoF) to perform complex maneuvers. The tendons are inserted in the bulb through fulcrum points positioned at lateral eyelets on the bulb surface and allow high forces to be exerted through the rigid over-tubes. The design is based on the concept of wire-driven parallel robots [2]. From their most distal aspect, the tendons are networked through and around the body of the scaffold and then congregate at the bulb 'neck' where they are bundled through one of the available internal channels of the scope. A motorized driving unit at the proximal-end provides computer-assisted actuation. The tendon-driven over-tubes are serving as attachment hubs for the tendons and are used to accommodate off-the-shelf flexible instruments and focused energy delivery devices. These may be delivered via existing internal channel(s) of the scope. The instruments may be immediately actuated by the above mechanism once docked within the over-tubes with a 'clip-lock-and-play' mechanism. Alternatively, the rigid over-tubes could be replaced by bespoke surgical instruments. Additional tendons could also be used to control the position of other equipment, such as an additional camera. The bulb is collapsible for extraction or extubation of the instruments. The concept is schematically illustrated in Fig. 2 along with an artistic impression of how a CYCLOPS system would look as part of a flexible or a rigid scope.

At the core of the CYCLOPS design lies a tendon-driven parallel robotic manipulator, delivered through its supporting peripheral structure. This is presented in more detail in the remaining sections.

B. Tendon-Driven Parallel Robotic Manipulator

One of the primary roles of the peripheral -bulb shaped- deployable structure, is to act as a semi-rigid scaffold for support and deployment of the tendons that control the surgical instruments. Fig. 3a shows a cross section of the structure as seen from one side, with only four of the tendons depicted. The tendon pairs are attached at a distance along the length of the rigid over-tube. Through small openings at lateral positions on the scaffold, the tendons can slide all the way to the back. The openings are placed in such a manner

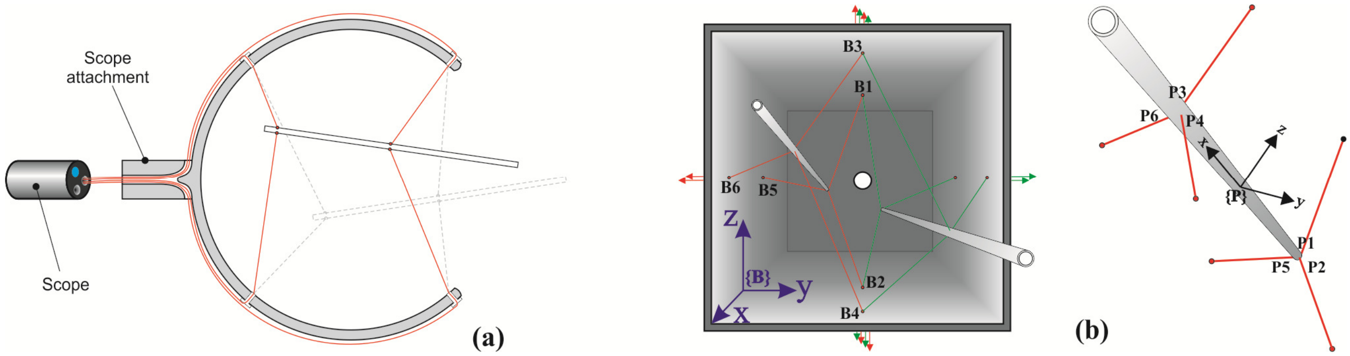

Fig. 3. (a) A cross section of the peripheral structure as seen from the side. The four tendons shown here are attached on the over-tube and through small openings on the scaffold they slide and congregate at the neck of the scaffold. One of the available scope channels is used to feed them all the way to the back at a motorized control unit. (b) An orthogonal scaffold demonstrates the tendon arrangement used with the CYCLOPS. The assignment of the base reference frame and the moving tool frame, as well as the positions of the feeding and attachment points of the tendons used to compute the kinematics and structural model of the system, are also shown. The tendon numbering for the single existing tool is also indicated.

that the tendons of each pair can exert antagonistic actuation forces on the rigid over-tube along different motion planes. This allows achieving different poses of the rigid over-tube when the length of the tendons is modified appropriately. Specifically, due to the unilateral property of tendons (*e.g.* they can only pull and not push), N number of tendons will allow the actuation of the over-tube at $N-1$ DoF [2]. In addition, it is critical to always maintain positive tendon tension during actuation in order to ensure the controllability of the moving over-tube. Since the tendon tension distribution is determined by the geometrical configuration of the system, different workspaces can be achieved by adjusting the position of the tendon attachments along the over-tube, as well as the location of the fulcrum points on the peripheral scaffold.

With the CYCLOPS, six tendons are used per over-tube providing five DoF manipulation, while two over-tubes are incorporated for bimanual control. This equates to twelve tendons being used in total. Fig. 3b demonstrates the concept using an orthogonal peripheral scaffold rather than a spherical structure for the sake of clarity. The fulcrum entry points at the top and bottom planes are shared by the respective tendons driving the two over-tubes. Currently, the CYCLOPS prototype is using a single over-tube. Since the design is symmetric, a second over-tube would be governed by the exact same considerations.

In order to determine the controllable workspace of the CYCLOPS, each over-tube is modeled as a cable-driven parallel mechanism according to [3]. The length of each tendon is calculated as the distance between the feeding point on the scaffold B_i and the corresponding attachment point on the rigid over-tube P_i: $\mathbf{l}_i = \overrightarrow{B_i P_i}$ ($i = 1, 2, ..., N$). To calculate the kinematics of the over-tube, these points are expressed in an inertial base frame {B}, while a moving frame {P} is attached to the centre of mass of the over-tube P. The position of point P can be expressed in the base frame as $\mathbf{p} = \{x \quad y \quad z\}^T$ so that the transformation between base and moving frame is given by:

$$\mathbf{T}_B^P = \begin{bmatrix} \mathbf{R} & \mathbf{p} \\ \mathbf{0} & 1 \end{bmatrix}, \tag{1}$$

where the rotation matrix $\mathbf{R}$ represents the orientation of the moving frame {P} with respect to the base frame {B} according to the Z-Y-X Euler angles α, β and γ. As discussed above, the tendons have to exert tension forces on the over-tube to keep it in equilibrium against any external wrench $\mathbf{f} = \{\mathbf{f}_p, \mathbf{m}_p\}^T$ applied during motion. By applying the equilibrium conditions at the centre of mass of the over-tube we obtain:

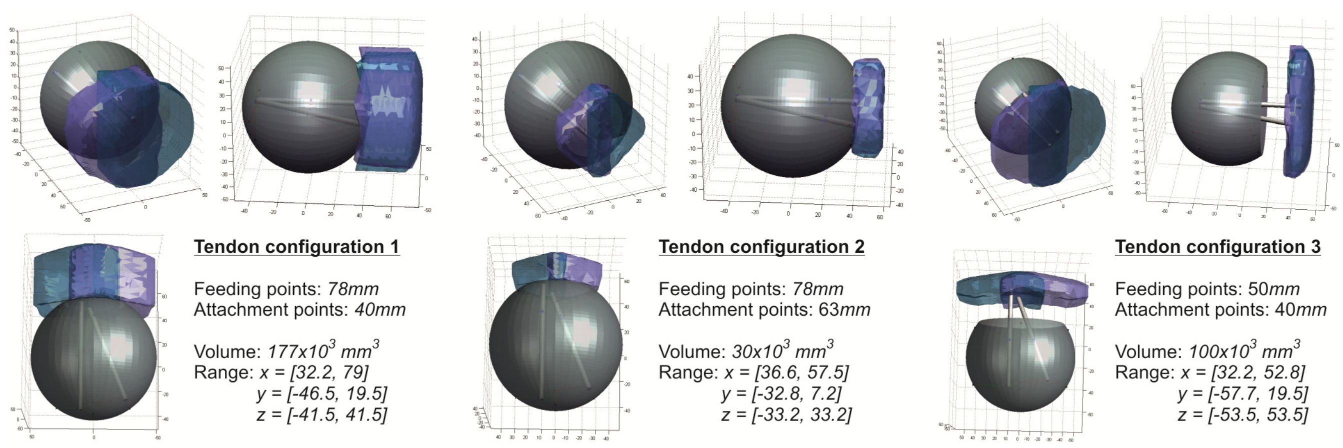

Fig. 4. Typical end-effector workspaces for a bimanual CYCLOPS for different tendon attachment distance and entry point distance configurations. The workspace volume of a single tool for each configuration is quoted, along with the corresponding workspace range on the x, y and z axis of the base frame. The overlapping workspace is also visible, signifying the ability of the tools to perform maneuvers requiring crossing into each other's workspaces.

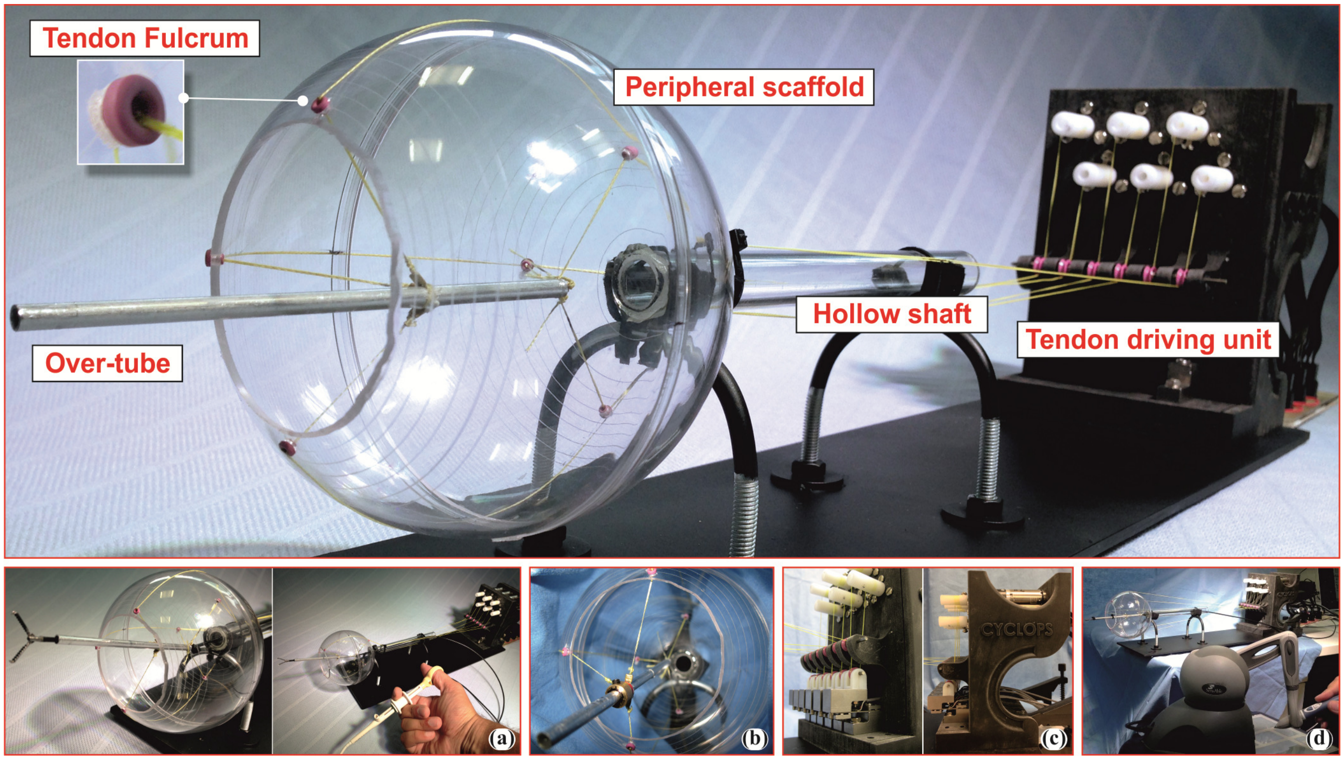

Fig. 5. The CYCLOPS working prototype at its early stage of development. (a) Flexible standard instruments can be inserted in the over-tube. (b) A sliding collet is used to allow adjustment of the tendons position on the over-tube. (c) Six load cells at the driving unit are used to measure tendon tension. (d) The CYCLOPS prototype is controlled by means of a haptic manipulator.

$$\mathbf{A}\,\mathbf{t} + \mathbf{f} = \mathbf{0}\,, \tag{2}$$

where $\mathbf{t} = \{t_1, t_2, ..., t_N\}^T$ is the tendon tension vector and $\mathbf{A}$ is called the *structure matrix* of the system and is given by:

$$\mathbf{A} = \begin{bmatrix} -\frac{1}{l_1}\mathbf{l}_1 & \cdots & -\frac{1}{l_N}\mathbf{l}_N \\ -\mathbf{r}_1 \times \frac{1}{l_1}\mathbf{l}_1 & \cdots & -\mathbf{r}_N \times \frac{1}{l_N}\mathbf{l}_N \end{bmatrix}. \tag{3}$$

The position of each tendon attachment point on the over-tube during motion can be expressed in the base frame as:

$$\mathbf{p}_i = \mathbf{p} + \mathbf{R}\mathbf{r}_i\,, \tag{4}$$

where the vector $\mathbf{r}_i$ defines the position of the attachment point $\mathbf{p}_i$ with respect to the centre of mass of the over-tube expressed in the moving frame {P}.

As discussed above, the controllable workspace of the over-tube is given by the set of poses satisfying equation (2) with $t_i \geq 0\ \forall i \in (1,\ldots,N)$. However, in real systems the tendon tension needs to be limited to a maximum $t_{\max}$ value to avoid breakage and also to maintain a small pretension $t_{\min}$, so that the solution of equation (2) is acceptable only if $t_i \in [t_{\min}, t_{\max}]$. The corresponding feasible workspace for left and right over-tubes can be found by solving a nonlinear optimization problem as described in [2]. In a nutshell, the algorithm first finds the highest and lowest tendon tension solutions for a number of poses of the rigid over-tube; if both solutions are within the allowable tendon tension range the corresponding pose is added to the feasible workspace, otherwise it is discarded. To highlight the effect on the workspace of different tendon configurations, the resulting CYCLOPS workspace for a minimum tension value of 0.01 N and a maximum of 120 N corresponding to three exemplar tendon configurations is shown in Fig. 4, where the external wrench is considered null.

C. CYCLOPS Working Prototype

At the time of writing this manuscript, the CYCLOPS prototype has a rigid scaffold, which is considered already deployed (Phase 4 in Fig. 2). Also, only a single over-tube with its six dedicated tendons is available, corresponding to the right-hand surgical tool of a bimanual system. The left-hand over-tube would require identical considerations to its symmetric counterpart, as discussed previously.

Fig. 5 shows the CYCLOPS working prototype. The peripheral scaffold is constructed using a clear polystyrene sphere, made up of two hollow hemispheres. These are commonly used for decorations. The external diameter of the sphere is 100 mm with a wall thickness of 1.5 mm. A 13 mm diameter hole is opened at the apex of one hemisphere and a hollow polystyrene tube is glued in place to allow flexible instruments to be inserted in the over-tube, as shown in Fig. 5a. Centered at the apex of the second hemisphere, a larger opening with a diameter of 52 mm is cut out. Six tendon fulcrum points are opened on the scaffold and 1 mm internal diameter ceramic eyelets are inserted to minimize the friction and smooth out the angulation of the sliding tendons. The exact position of the fulcrum points is indicated in Fig. 3.

For the tendons, nylon braided fishing line is used with a breaking strength of 14 kg. Brass crimps are used to attach the tendons onto the aluminum over-tube via through-holes at its proximal end and sliding loops at its more distal end. A screw-tightened sliding collet allows easy adjustment of the distal tendons position along the axis of the over-tube (Fig. 5b). The over-tube has an external diameter of 4 mm.

The scaffold and the shaft are mounted on a base together with a motorized tendon-driving unit. The unit uses six brushless DC servomotors with integrated CAN controller and a 25:1 ratio gear-head (Faulhaber 2232S024BX4 CCD-3830 + 22F 25:1). The motors' maximum torque is lowered by enabling the current limiting function on the built-in motion controller. Each motor actuates a 9 mm diameter Delrin® wormscrew used to control the length of the corresponding tendon. At the base of the driving unit, a series of six full-bridge thin-beam load cells (Omega LCL-010) are mounted. Miniature ceramic bearing rollers are used to transmit the tendon tension to the load cells as shown in Fig. 5c. For monitoring the tendon tension, an InstruNet INET-100HC data acquisition unit is used. The device allows 8 differential analogue inputs to be digitized and transferred to a computer over a USB controller.

For controlling the CYCLOPS, a Geomagic® Touch™ (formerly Sensable Phantom Omni) haptic device is used (Fig. 5d). All software is written in C++. The whole system is easily portable and a single laptop is used for connecting the master manipulator, the CAN controller for the motors and the data acquisition unit for the load cells.

At the time of writing this paper, position control of the tendon-driven over-tube is achieved on the basis of simple geometrical considerations. Under this control regime, the motion commands from the haptic device are translated into tendon length variations according to the inverse kinematic model of the system and then sent to the motors for appropriate actuation of the corresponding wormscrews. As already discussed, for efficient control of tendon-driven parallel robots, force-control is required instead to ensure that the tendon tension vector is always positive. Although this is not implemented in the current prototype, the information acquired from the load cells will be used at a later stage for this purpose. Nevertheless, even at its present stage of development the CYCLOPS is able to demonstrate its operational capabilities, which are discussed next.

III. Operational Capabilities

To further highlight the capabilities of the CYCLOPS, a number of experiments have been carried out. The first is a standard peg-transfer task from the Fundamentals of Laparoscopic Surgery (FLS). Since only one instrument is available at this stage, the task had to be slightly modified by omitting the mid-air object transfer from hand to hand. Instead, a single instrument has been used to transfer an object back and forth between four pegs, performing eight peg transfers in total. Control of the instrument is achieved using the haptic manipulator. For grasping, a standard flexible endoscopic forceps is introduced through the CYCLOPS hollow shaft into the tendon-driven over-tube. Opening and closing of the grasper is manually achieved by the user using the left hand to control the thumb-ring on the handle of the forceps (Fig. 6 top). During this task the execution time has been recorded along with the number of successful transfers.

In previous sections, the CYCLOPS workspace was characterized and it was discussed how it is influenced by changes in the tendon configuration. The second set of experiments aims to investigate the force-exertion capabilities of the CYCLOPS and how these are affected by changes in the tendon configuration. An external load cell is used to measure the force exerted by the tool end-effector in six directions when the over-tube is aligned with the base coordinate system (Fig. 3b). The load cell is rigidly attached at a fixed position with respect to the CYCLOPS body (Fig. 6 bottom). For most measurements, the end-effector is attached to the load cell by means of hooks and a string of the same material as the tendons. Only for the pushing measurements in the +X direction, the end-effector is directly pushing against the load cell. While the user is controlling the end-effector motion in a required direction, the external load cell readings are recorded, along with all tendon tensions.

For pair-wise comparison with the respective workspace investigations shown in Fig. 4, the two tendon configurations that have been tested are with the tendons attached on the over-tube at 40 mm (narrow configuration) and at 63 mm (wide configuration) apart. The proximal tendons are kept in the same position in both cases, which is close to the over-tube entry point. The exerted force measurements are taken at the end-effector position located 85 mm from the proximal tendons. All force measurements have been initiated with the over-tube starting roughly from the same initial position aligned with the main diameter of the spherical scaffold.

IV. Results

Being at a very early stage of development, the CYCLOPS system does not allow for proper validation using standardized tests, such as the FLS. Nevertheless, the peg-transfer task described above was routinely carried out successfully, achieving very low execution times of a few seconds with 100% success rate. Although at times it felt somewhat challenging reaching certain configurations with the CYCLOPS instrument, most of the time and for the majority of the hand maneuvers, the desired response could be achieved. This behavior was expected, given the lack of

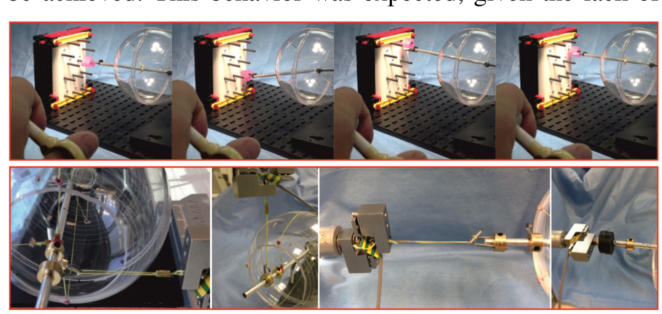

Fig. 6. At the top, the peg-transfer task, showing the 4 pegs used for the transfer. The thumb-ring that allows the user to actuate the grasper's opening and closing is also visible. At the bottom, from left to right, the experiments showing forces assessed in the +Y, +Z, +X and –X directions.

force-control of the tendons. It is anticipated that when this is in place, any manipulation uncertainty will disappear. A difficulty of the task was also related to the bimanual coordination between the master manipulator controlled with the right hand and the thumb-ring that was controlled with the left hand. Also, the task was further complicated by the visual-motor misalignment caused by the lack of aligned views that an onboard camera would normally provide.

The next set of experiments helped to vividly demonstrate the unparalleled force exertion capabilities of the CYCLOPS. The plots in Fig. 7 show the recorded force on the tool end-effector along with the respective tendon tensions. The six plots on the left column correspond to the narrow tendon configuration, while the six plots on the right are obtained with the wide tendon configuration. Each row represents one of the six directions along which the force exertion capabilities of the CYCLOPS were tested. The high force capability of the system becomes immediately apparent. The highest recorded force is over 6.5 kg (65 N) for the narrow configuration on the positive X axis, while the minimum recorded value is close to 0.7 kg (7 N). TABLE I shows the maximum forces achieved in all directions for both configurations. From the force plots, the necessity of implementing a force-control framework becomes obvious. This is clear, by the large variability of the tendon tensions during the execution of a single experiment. Control of the tool in the required direction is achieved by the master

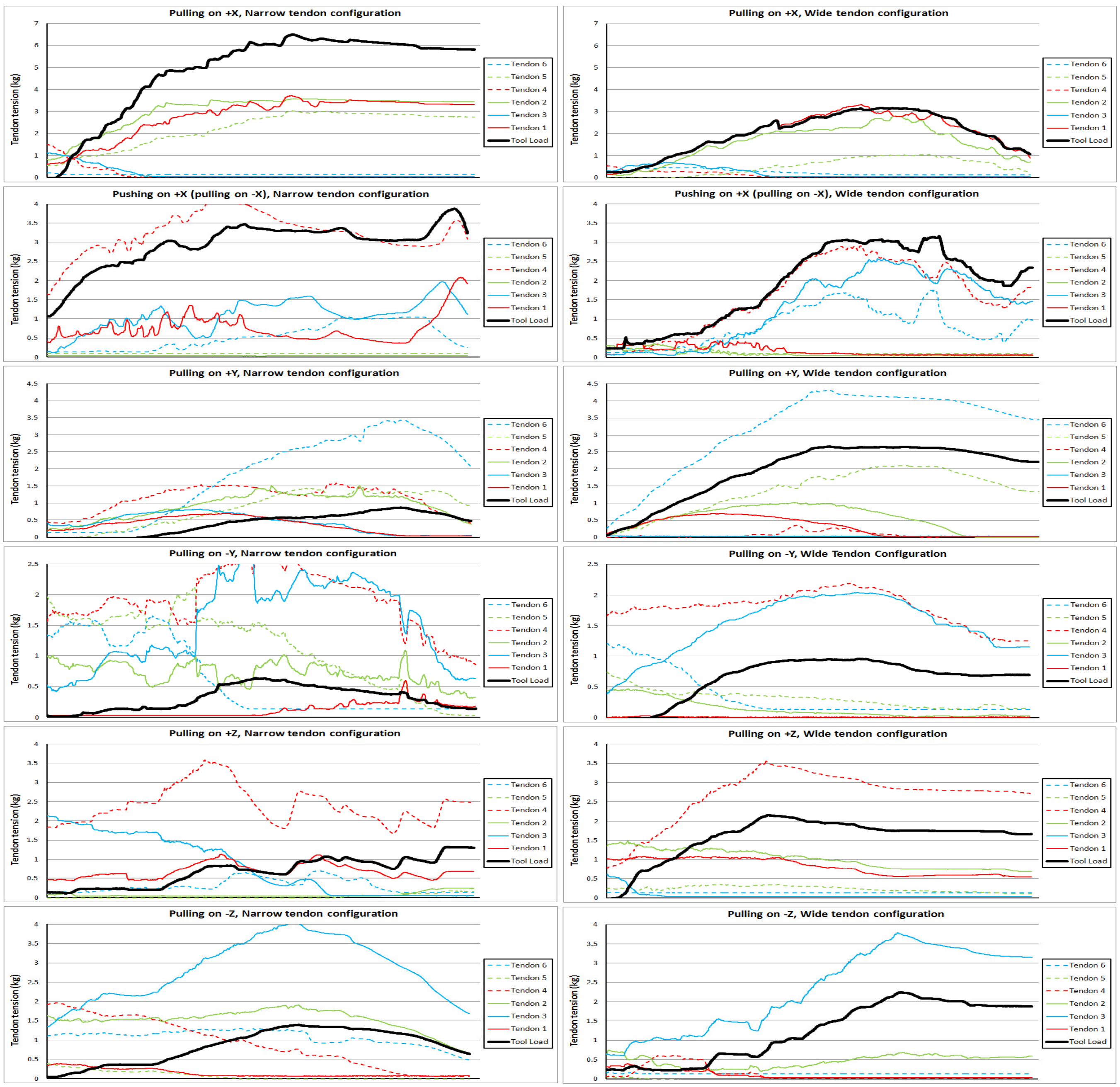

Fig. 7. The thick black line represents the recorded force on the tool end-effector. Colored lines correspond to the tendon tensions. The six plots on the left column correspond to the narrow tendon configuration, while the six plots on the right are obtained with the wide tendon configuration. Each row represents one of the six directions along which the force exertion capabilities of the CYCLOPS were tested

TABLE I. CYCLOPS force exertion capabilities in all directions. The force direction is regarded as the load pulling on the tool

Direction of applied force	Max exerted force in kg (N)	
	Narrow - 40 mm	*Wide - 63 mm*
+X	6.5 (65)	3.2 (32)
-X	3.9 (39)	3.2 (32)
+Y	0.9 (9)	2.7 (27)
-Y	0.7 (7)	0.9 (9)
+Z	1.3 (13)	2.2 (22)
-Z	1.4 (14)	2.2 (22)

manipulator with no force feedback. Consequently, the user is oblivious to the amount of force exerted by the tool, or the motors torque capability at any given time as they keep translating the master in the desired direction. While some motors stall due to reaching their maximum capacity (around 3.5-4 kg from the plots), some others keep rotating without affecting the length of the corresponding tendons in an attempt to follow the inverse kinematics model. This is visible in almost all plots where tendon tension often drops to zero. What also becomes immediately apparent is that different tendon configurations endow the system with different characteristics in terms of its force capabilities. One tendon configuration favors certain directions while another configuration favors different directions. Another observation is that relatively small forces are observed when the load cell is pulling the end-effector in the –Y direction. This can be attributed to the initial position of the over-tube, which is close to the main diameter of the spherical scaffold. Near this position, the angle between tendons 3 and 4 (see Fig. 3b) is obtuse which means that the amplitude of the composite force vector is small.

There are a lot more conclusions that could be drawn from the force plots. The most important at this stage is that the CYCLOPS possesses high force exertion abilities and that for a more exhaustive assessment of its operational capabilities force-control will have to be implemented.

V. Conclusion

In this paper we have introduced the CYCLOPS, a novel robotic system for endoscopic surgery. Even at its very early stage of development, the design is able to demonstrate a number of qualities and features that make the CYCLOPS stand out from other existing systems. Preliminary investigations have demonstrated its high force exertion capabilities. With forces as high as 65 N and no lower than 7 N it is already more powerful than any existing design that has come to the author’s attention. It is expected that when force-control is implemented, the low end of the force exertion capabilities will be improved. Also, the flexibility of the CYCLOPS in modifying the force and workspace profiles makes the proposed design ideal for adaptation to different surgical requirements. A variable size peripheral structure does not invalidate the working principle of the design while at the same time allows customization for different surgical requirements and lumen sizes.

Full evaluation of the capabilities as well as the limitations of the system requires further investigations. However, due to its principle of operation and the simplicity of the design, the CYCLOPS already shows its potential. Some of its strengths are: *reliable actuation*, *low cost*, *low weight*, potential *MRI compatibility*, and *reliable force feedback* for haptics due to the direct force mapping principle involved.

On a less dithyrambic tone, there are still a number of design issues to be resolved before the CYCLOPS can find its way into clinical practice. One of the major research areas we are already working on is related to the design of the peripheral structure. In its original conception, the scaffold is considered as a purely inflatable mechanism that can be deployed and collapsed. This way, the “bulb” can also be used for intracorporeal space creation, tissue suction and invagination, and subsequently tissue extraction. While research in this direction is undergoing, preliminary investigations have shown that the spherical and continuous structure is ideal for spreading and balancing out the forces exerted by the tendons, offering stability and high force capabilities.

In terms of easily switching between different force and workspace profiles, for instance from one that favors force in a given axis to one that favors large workspace, it was shown that one way of achieving this is by changing the position of the tendons along the tool. Although this functionality seems easy to incorporate, it is expected to require considerable research and development effort.

On a closing remark, we need to mention the lack of rotation of the CYCLOPS over-tube around its main axis, as due to the existing configuration only 5DoF are feasible. Although not yet assessed to what extent this impedes task execution, there are some potential solutions to this limitation. One approach would be to incorporate an additional tendon, bringing the total number to 7. Another option would be using a bespoke motorized instrument in lieu of the existing over-tube. There are also other options which are being currently investigated.

The aim of the CYCLOPS concept is to provide a platform that enables new techniques like SILS, NOTES and NOES to be more realizable in the short-tem in a clinical setting. This is proposed by a unique and highly original design that is adaptive to the existing laparoscope or flexible endoscope. This approach promises a more immediate and accelerated route to clinical translation not only through endearing low-cost and adaptive features, but also by directly addressing several major existing barriers in platform design.

Acknowledgment

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