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EasyLap-New Robotic System for Single and Multiple Access Laparoscopy Using almost only Traditional Laparoscopic Instrumentation

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Abstract

A new robotic system for single and multiple access laparoscopy is presented, using almost only traditional laparoscopic instrumentation, including very small diameter instruments for babies, based on an evolution of previous research by this research group. Main idea behind this system is to make simple its use, for instance instructing the optics to point always the tip of the instrument on which the surgeon is acting in a totally automatic way; a second important feature is the ability to guide also the motion of the instrument on which the surgeon is acting so that it corresponds to the joystick motion as seen from the monitor. All instruments are traditional, but for a special edition of SAL Twin Forceps, and a second instrument similar to the wrist of da Vinci but reusable and sterilizable since it uses only rods and gears for its motion.

Keywords: Robotized System for Traditional Instrumentation; Automation of Optics Motion.

1. Introduction

The paper presents a new robotic system for single and multiple access laparoscopy which uses almost only traditional laparoscopic instrumentation, including instruments of very small diameter for babies, which, at present day, is impossible with other systems. The research is based on an evolution of previous research by this research group, deriving from the experience of Navi-Robot [1-5], DARTAGNAN [6-9] and the study of special end effectors for laparoscopy [10-12]. One of the first robotized surgical systems applied to in the laparoscopic field was Aesop [13] which guided the optics on voice command while Zeus was moving the instruments, both absorbed by da Vinci [14-21] that is so far the winner. However while this system is diffused in the States and weirdly enough in Italy, in the rest of the world, and in Europe in particular, its sales are low mainly, but not only, for cost reasons, another problem being the need for a long instruction period. A number of other systems were proposed by different research groups, such ad MiroSurge by DLR Institute of Robotics and Mechatronics, Germany [22], similar in concept to Da Vinci being multi arm (as our proposal), with some advantage on an easier access for the surgeons to the operatory table, but also in this case, using proprietary instrumentation, or SOFIE [23] other robot made in Eindhoven, again a robot da Vinci type using again proprietary tools, or SPORT™ Surgical System briefly described in [24], new system by Titan Medical, that seem very near commercialization.

Socrates [25] instead is made to ease communications between doctors located in different places anywhere in the world, this may help, but is not a surgical robotic system.

A different concept is presented by Sprint [26], a two arm system for SILS, that is meant to be introduced through a bigger orifice directly inside the patient, thus again using only its own tools, in this being similar to SAIT (Samsung Advanced Institute of Technology, 138 Gyeonggi-do, Korea), that carries also the optics and a third operatory arm [27]. Complete recent reviews of the various robot are provided in [28-29].

2. The Robotic System

The actual system under development by our research group presents four to six arms fixed on a common base (usually five), each being a passively self balanced six degrees of freedom (DoF) fully actuated system but for the arm dedicated to the optics which presents only four hinges actuated, with the last two that are simply equipped with encoders. In all cases the axes of the last three DoF will cross forming a spherical hinge.

Each arm presents a first joint (1) having vertical axis, while, the second joint (2), horizontal, belongs to a parallel arm four bar link that allows changing the vertical position of the end effector while maintaining hinges (3) and (4) with vertical axes. Joint (5) again presents horizontal axis, while the last hinge axis is perpendicular to the previous. Moreover, the presence of counterweight (7) completely balances the entire structure. A force sensor (8) is mounted on the end effector, that ends with a male quick connector (9), bearing also the electronic connectors.

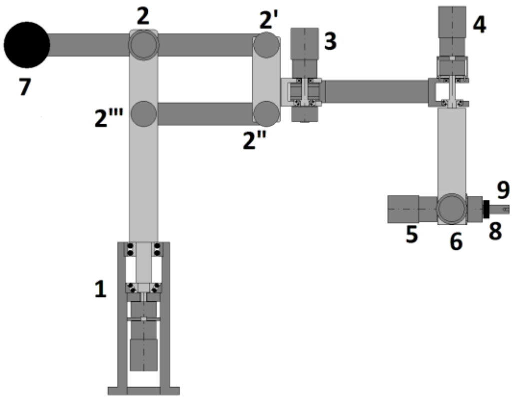


Figure 1. Scheme of an EasyLap arm

As can be seen in Figure 1, the first three degrees of freedom (1-3) allow positioning the fourth hinge in any position in space in a cylindrical space around the first vertical hinge, while the last three degrees instead allow positioning the final end effector with any direction within the workspace. Clearly special actuators are needed to mount each instrument on the end effector, also because their position may change depending on the surgery. They are obviously reusable, hold both motors and control electronics, present a female quick connector that allows determining the position of the instrument in a unique way. Each joint is moved by a Maxon motor-reducer-relative encoder group, whose angles are measured by a 16 bit digital encoder being each joint controlled by a Maxon Epos2 board connected in CAN®open. On all the sixth end effector are mounted the instruments actuators (two controlled motors for traditional instruments, four for SAL Twin Forceps and the wrist instrument).

Figure 2 shows the CAD model of a possible 5 arm version of EasyLap, being the five arms mounted on a single chart that can be moved over the surgical table to dominate the surgical theatre, with the central arm (23) hosting the optics.

At the beginning of the surgery, it is first necessary to select the sterile instruments to be used, mounting them on the appropriate motorized adapter. Then, having placed all trocars on the abdomen and moving over the chart of Figure 2, each instrument has to be introduced in its trocar, penetrating just till the level of the patient's skin, moving the relative arm that will follow the small forces applied to move it. After positioning all of them, simply pressing start surgery, the system will record the coordinates of all trocar entry points. From now on the system knows that it will always have to leave this point fixed, being able to vary depth and inclination of each instrument, under the doctor control. Clearly each instrument may be always rotated about its axis.

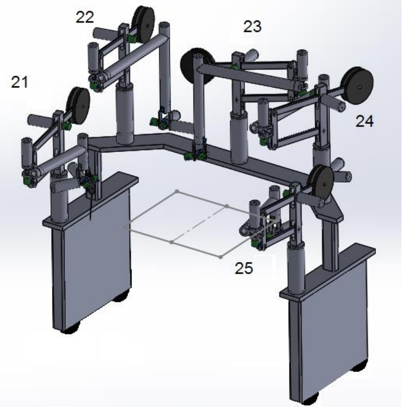


Figure 2. A possible 5 arm Easy Lap version

Note that being all instruments mounted around the abdomen of the patient, and being many of them, it is very important that they do not disturb each other and in particular that the adapters stay well separate. This causes the necessity to control separately the instrument's cannula rotation from the joint's position. Moreover, since not all the traditional instruments allow rotating the handle with respect to the surgical instrument, two different adapters will be needed. In every case it is possible to keep the body of the adaptor oriented always radially, while moving the instrument as requested.

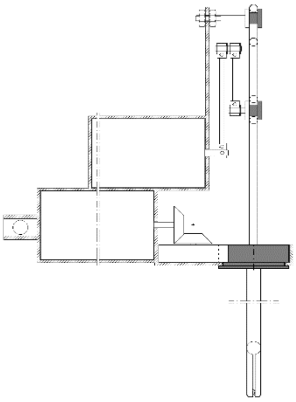


Fig. 3. Scheme of an adapter for traditional instruments able to rotate the handles with respect to the cannula

Next Figure 3 shows a possible adaptor for a traditional instrument, in which one motor is dedicated to opening and closing the forceps, while the second rotates the instrument's cannula. Naturally many are the possible configurations in this case, this is just an example, where the dark components must be sterilized each time.

As far as the adapter for instruments needing four controls (cannula rotation plus three actuators), such as SAL Twin Forceps [30-31] or wrist, or any other, this is presented in the Figure 4. On the left side we observe the position of the four motors, each of which has a spur gear (all identical) mounted on its exit shaft. On the side of each gear, a second gear meshes with it (the red circles, always on the left), so that their axes lay in a plane. Passing to the sketch on the right side, in which the motors are not aligned just put in evidence the fact that they not coplanar, note that each red spur gear, held in position by suitable bearings, gives origin to short shafts on which are mounted incremental encoder disks (green) and a bevel gear, which mesh with other spur gears, the first being fixed to the special instrument cannula. The following, free to rotate with respect to the instrument's cannula, transmit the rotation to a second set of bevel gears, mounted every 90° and fixed to internal mechanisms actuating the three instrument controls.

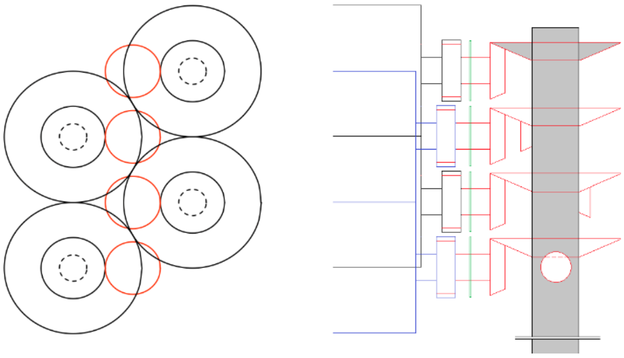


Figure 4. Adapter for instruments needing four controls

Notice that the motor dedicated to instrument's rotation moves the cannula, while all other can move a single control. However, if the cannula is rotated, all other three motors must rotate in the same direction and speed in order to preserve the configuration of each control. The robotic edition of SAL Twin Forceps differs only in the portion that substitute the handle, with the second and third bevel gear of figure 4 being connected on a small drum around which is wrapped around the cable that controls forceps opening, while the last bevel gear is coupled internally to a small spur gear acting on a rack, which commands opening and closing of the instrument's arms.

Fig. 5 shows the EasyLap NWrist, similar to the wrist of da Vinci [32] but reusable and sterilizable since it uses only rods and gears for its motion and whose initial portion is identical to the previous. Let's start to examine the instrument's tip. As can be seen, the two elements of the forceps/scissor open symmetrically thank to the use of five tiny spur gears, 1 and 3 fixed on the same axis. Furthermore the distance between gears 1-2 and 3-5 is identical, being gear 4 idle, used to invert the motion of gears 2 and 5, and the two elements of forceps/scissors fixed to gear 2 and 5. Motion to gear 1 is produced by gear 6, which is partly spur and partly bevel, actuated by 7, sector of bevel gear. In parallel, a second sector of bevel gear, 8, acts on the bevel part of gear 9, which, with its portion spur, moves gear 10, fixed to the small frame holding gears 1 to 5. Rotating then only gear 6 by 20°, we obtain the opening of forceps/scissors by 40°, rotating in the same direction and quantity gears 6 and 9, we obtain configuration d with closed forceps, rotating further gear 6 the forceps opens even if inclined by 90° and in the direction of the same curvature. Gear 6 is actuated by rods connected to a first external motor controlling rotation of wheel 11, while wheel 12 acts on 10. Finally to obtain configuration b is necessary to act in the same time on wheels from 11 to 13, last one being connected via tiny rods to frame 14, and, rotating further wheel 11 we obtain forceps opening, in the direction perpendicular to the curvature. Motion transmission between the initial wheels and the final gears is performed with tiny rods.

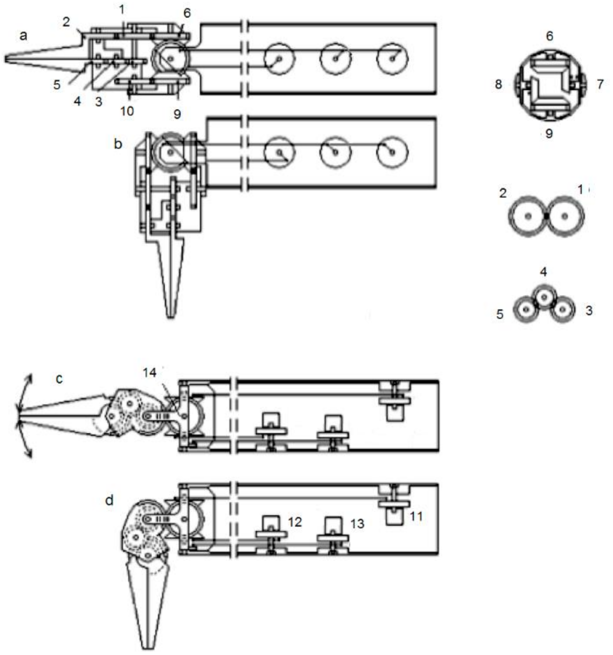


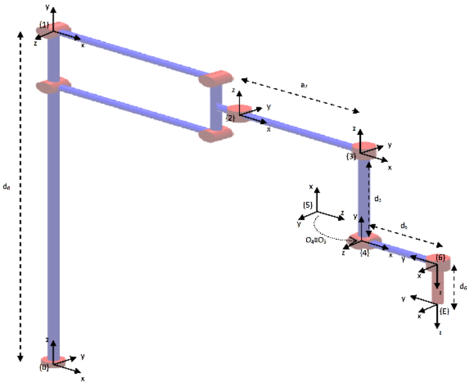
Figure 5. EasyLap version of Wrist instrument.

Naturally each adaptor will receive its commands via CAN®open so that there is only the need to add the DC power supply, since the controlling board will be present on the adaptor.

Passing to the console, only two joystick will be present, plus the start button, four buttons to select the instrument one wants to control, and a number of knobs to control the various options. This part is clearly not yet well defined, we will need the feedback from the users, to understand which is the simplest way to transmit the message.

3. EasyLap kinematic model and algorithms

Fig. 6 shows the kinematic model of an EasyLap arm, with relative Denavit Hartenberg [33] transformation table for the serial portion of this robot.

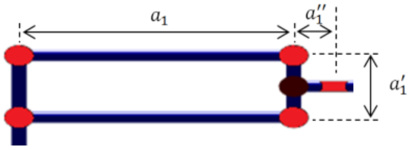


Transf	θ_i	d_i	α_i	a_i
0→1	q_0	d_0	$\pi/2$	0
1→2	D-H not applicable to closed loop kinematic chain			
2→3	q_2	0	0	a_2
3→4	q_3	$-d_3$	$\pi/2$	0
4→5	q_4	0	$\pi/2$	0
5→6	q_5	d_5	$-\pi/2$	0
6→E	q_6	d_6	0	0

Figure 6. EasyLap kinematic model and DH table for the serial part of this robot

For the closed loop kinematic chain, showed in Fig.7, it is not possible to apply the canonical Denavit-Hartemberg method. The transformation between frame 1 and 2, was so calculated by using the Denavit-Hartemberg method extended to closed loop kinematic chain obtaining the transformation matrix of Figure 7.

As we mentioned before, to make the system really easy to use, two problems are to be solved. First problem, the automatic pointing of the optic on the instrument in use, when the doctor passes to a different one. In fact the tip position of each instrument in terms of quaternion, as the result of the product of the sequence of quaternions representing in terms of the sequence of joints, is always known. However not all the optics have straight vision, some have vision inclined by 30, 60 or even 90 degrees. Thus, in the case of straight vision, it is enough to move the optic computing the directional cosines of the line that joins the tip of the instrument to be observed and the entry point of the optic into the patient abdomen, and move the arm accordingly. More complicate may be the case in which the optic presents an angular deviation, whose direction of observation is also known, as always in terms of last end effector quaternion. Now we have three points to take into account, the tip of the instrument to be observed, the tip of the optic and the entry point in the patient's abdomen. First we have to bring the observation direction to lie on the plane passing from these three points, rotating the optics, secondly we might have to change inclination of the optic to center the vision on the point of interest. Moreover, the global surgical field (previously recorded) will be shown in a second image, circling the region actually treated.



$$T_2^1 = \begin{bmatrix} 1 & 0 & 0 & a_1'' + a_1 \cdot \cos(q_1) \\ 0 & 0 & 1 & -a_1' + a_1 \cdot \sin(q_1) \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Fig. 7. Transformation for closed loop chain of an EasyLap arm

Similarly, since the position of the optic is always perfectly known in terms of directional cosines, which are associated with the camera position, then moving the joystick in a direction with respect to the monitor, means to be willing to move the instrument in the same direction, hence supplying the system the desired direction of motion. Thus it is easy to compute the new position of the tip of the instrument using line's parametric equations starting from the actual instrument's tip coordinates, then remembering that the entry point into the patient abdomen is a fixed point, we obtain the new instrument orientation, and from this, via inverse kinematic, the set of new joint parameters to be reached linearly. Of course it seems a very long process, but once programmed in C, it takes nothing. And this allows establish the instrument's direction of motion so as to correspond to the direction required as seen in the monitor frame of reference.

Finally this system, having five arms on which is possible to pre-mount a number of different tools, including for instance a stapler, can be used especially for SAL, allowing to extract the surgical instrument to replace it with the stapler in a quasi automatic way (it will extract the instrument, reposition the new tool on the trocar, and re-enter the abdominal cavity under surgeon control).

4. Conclusions

This is at the moment just a first description of this system, that will be built and tested during the next two years, after presenting it to our Regional Authority for funding. In fact it derives from our previous experience thus is just not a dream, even if the control electronics for the adaptors is still to be developed. Many components will be built using 3D printing both in stainless steel and plastic, while the arm's structure will be mainly in aluminum. A first Italian patent application has also been presented [34].

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