Bitrack: a friendly four arms robot for laparoscopic surgery

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INTRODUCTION

For years, robotic laparoscopic surgery has motivated research and initiatives with the development of robotic systems offering different kind of solutions, being Bitrack a new option. At present the market is dominated by DaVinci, which has become a benchmark in this speciality. Laparoscopic robots offer precision and accessibility since their instruments are endowed with 3 DoF, for their orientation, which are missing in standard laparoscopy. This paper presents the Bitrack system, which is a new laparoscopic surgical robot, designed at UPC, and currently undergoing the process of certification by a spin-off created for its exploitation, RSS. This new robot aims to obtain the same benefits and accuracy as the current benchmark but overcoming some dependencies that current robotic surgery poses. Many reports on studies that evaluate the contribution of robotics do not doubt on the improvements achieved with the use of robots in what refers to surgical quality and that more complex surgeries can be addressed than those performed by laparoscopy [1, 2]. The Bitrack system apart from these clear contributions of robotics also provides the concept of hybrid surgery. This concept implies the capability of performing an intervention alternating standard laparoscopy with other robot assisted phases according to the needs in each stage of the procedure. This performance has been achieved thanks to the Bitrack friendly design which allows a quick interchange of robotized instruments by their manual counterparts, less than a minute each, using the same conventional trocar. This paper presents the robot architecture and the experimental results achieved with the operational prototype.

ARCHITECTURE

Bitrack has been conceived aiming to achieve an easy and quick set-up by providing just the minimum redundancy necessary to avoid collisions between the four arms, fig.1. Redundancy and collaborative control are necessary for and interactive human-robot system [3]. However, a high degree of redundancy generates a too high redundant number of configurations. The challenge has been defining a kinematic architecture that optimizes the compromise between collision avoidance and intuitiveness in the manual guidance along the setting-up of the operational work space.

Being the set-up a manual operation, that is, the insertion of the four surgical instruments into the corresponding trocars by means of gestural movements made by the medical staff, this operation should be as easy and friendly as possible. A redundant degree of freedom implies unidimensional pose alternatives, which is intuitive for a human. More degrees of redundancy involve a movement with higher dimensional pose alternatives, but not so evident for manual operation.

The Bitrack system, fig.1, consists of a four-arms robot mounted on a column, which is provided with a vertical linear DoF. Each arm can pivot around the column independently from the others. The arms, with two different architectures are placed respectively in two levels.

Fig.1. The Bitrack system

All the arms operate with an elbow outside configuration, but the two upper arms have a SCARA type architecture to avoid interferences with those below. These two architectures are conceived to be able to operate in a quasi-coincident work space minimizing interference between the four arms. The upper arms can operate internally or externally with respect to the lower arms and can be used indistinctly for camera guidance or as auxiliary arm. The lower arms are the operational ones. Fig.2 show the kinematics of the two types of arms.

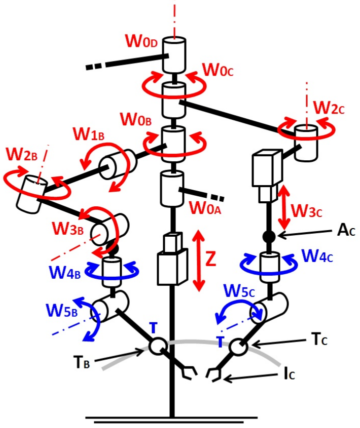

Figure. 2. Kinematics with indication of the DoF of the two kind of arms (B and C)

The DoF of the lower arms are three rotations: W_0 around the column axis and W_1 and W_2 which allow the wrist $A(x_A, y_A, y_A)$ to reach any position in the working space. W_3, the fourth joint adds a degree of redundancy allows reaching the target position in different orientations and thus optimize the shared workspace by shifting the other joints conveniently. The wrist supports the instrument (I), which movement is restricted as it pivots over the trocar

$T(x_T, y_T, z_T)$. Once in the target position, W_4 and W_5 provide the orientation compatible with the trocar.

The difficulty to control the coordinates of the instrument tip $I(x_I, y_I, z_I)$ compatible with the intermediate point T, the trocar, requires knowing its position. DaVinci solves this problem by subjecting the trocar with active joints. Doing this way, the trocar keeps steady all along the intervention and thus not posing a problem to the kinematics computation. In the Bitrack system, to ensure its continuous adaptation to the patient and transient variations in gas pressure in the abdominal cavity and at the same time facilitate the set-up, these two DoF are passive and therefore they do not force the movement of the operator who can smoothly insert the instrument. By freeing the trocar, its position becomes a variable, but the Bitrack system continuously computes its position with enough precision. The free movement of the trocar with respect to the arm, although requiring its computation to control teleoperation, avoids strains on the abdominal surface that can produce bruising and also gas leaks during the procedure. In addition, the Bitrack architecture enables the use of conventional trocars and thus the possibility of changing from robotic surgery to standard laparoscopy at any time during an intervention.

The architecture of the upper arms, also shown in fig. 2, has no redundancy and joint W_3 is changed from angular to linear, a vertical displacement to minimize volume occupancy. The lower arms, with redundancy, are those that avoid collision with the upper ones. A simulation of this architecture, Fig. 3, has allowed modelling the working volume that show an accessibility for each instrument of about a 35x45x55 cm spheroid.

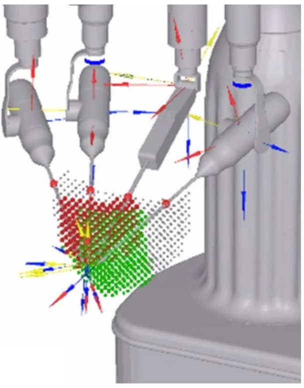

Figure. 3. Working volume

RESULTS AND DISCUSION

With this architecture, the Bitrack system becomes very versatile and offers an easy set-up process having reduced as much as possible the redundancies that avoid collisions. Instead of the multiple redundant DoFs of DaVinci, which provide more configurations free of collision in broader spaces, Bitrack has only one redundant DoF for each lower arm, in addition to the common DoF for the Z movement of the column that supports the four arms. However, in the set-up, when the surgeon or medical staff should take decisions on movements dealing with redundancy of the arms, the additional DoFs of redundancy increase the time to reach an acceptable arms configuration and without guarantying reaching an optimal solution. The Bitrack architecture simplification thus results in a shorter set-up time, but also in a smaller occupancy in the O.R, less weight and less cost. From the long evaluation phase in the experimental operating room, with animal models (mini pigs), the insertion and retrieval of instruments has been of 1,6 minutes in average (considering that some of them didn't have previous experience with Bitrack) in front of the 20 minutes that can be achieved with the Da Vinci Xi model after a training course. The quick interchange of instruments, together with the more reduced space occupancy in the OR makes the combination of robot and manual surgery feasible. This hybrid surgery allows a significant reduction in intervention time as many surgical tasks that do not require robot performance are executed quicker manually. Thus, the main contribution of Bitrack is not improving efficacy, since precision is no the problem in surgical robotics, but efficiency, understood as a balance between value and cost.

The architecture with multiple arms on a unique column has been chosen in front of other solutions as, Titan or CMR with configuration one column - one arm, since it is a more compact solution that occupies less space in the O.R. when four arms are needed.

The Bitrack system has been extensively tested in the experimental operating room Fig 4, in renal, hepatic and gynaecologic surgeries, as well as other less frequent surgeries that surgeons wanted to test, achieving a considerable reduction in operation time compared to fully robotic surgery.

Figure. 4. The operational Bitrack system performing a surgery in the experimental Operating Theater.

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