A novel robotic platform for single-port abdominal surgery

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Abstract. In this paper, a novel robot-assisted platform for single-port minimally invasive surgery is presented. A miniaturized seven degrees of freedom (dof) fully internalized in-vivo actuated robotic arm is designed. Due to in-vivo actuation, the system has a smaller footprint and can generate 20 N of gripping force. The complete work envelop of the robotic arms is 252 mm × 192 mm × 322 m. With the assistance of the cannula-swivel system, the robotic arms can also be re-positioned and have multi-quadrant reachability without any additional incision. Surgical tasks, such as lifting, gripping suturing and knot tying that are commonly used in a standard surgical procedure, were performed to verify the dexterity of the robotic arms. A single-port trans-abdominal cholecystectomy in a porcine model was successfully performed to further validate its functionality.

1. Introduction

In conventional open surgeries, large incisions are often made to allow surgeons full visualization of the targeted surgical site but this is often associated with increased pain, blood loss, possible risk of infection and prolonged hospitalization to the patient [1]. Computer-assisted robotic minimally invasive surgery (MIS) has become increasingly popular over conventional open surgical procedures as it can allow dexterous manoeuvrability of surgical instruments within the body cavity through small incisions [2]. Typical MIS procedures with existing technologies require multiple small incisions or a single incision for the insertion of surgical instruments [3].

In multi-port systems, more than one incision is required to insert the laparoscopic instruments, camera and additional auxiliary surgical tool inside the body. The surgeons acclimatize themselves to operate these systems through training, despite inadequate workspace and poor ergonomics (limited space) that makes certain manipulations difficult [4]. As the motors in these systems are externally driven, re-positioning of the laparoscopic instruments during the surgical procedure is difficult and thus require more incisions. In a more recent development, the instruments for the da Vinci Xi system (Intuitive Surgical, Inc.) can be repositioned, however, this is for multi-port access only [5].

Single-port robot assisted surgical systems is a technological advancement that enhances the existing benefits of MIS. In these systems, only one incision (usually through the umbilicus) is required to reach the surgical site. Despite potential advantages of single-port systems, several challenges still exist such as poor triangulation of surgical instruments, poor working ergonomics for the insertion of multiple instruments into the abdominal cavity and the inability to apply off-axis forces [6].

Recently, various groups have developed single-site surgical robotic systems, such as the da Vinci Sp system from Intuitive Surgicals Inc., SPORT surgical system from Titan Medical Inc., single-port
system from Samsung Advanced Institute of Technology [7,8]. In systems that have external-motor driven arms, the system footprint is usually bulky and it is difficult to reposition the arms, however, torque output is higher as compared to compact systems [9].

The concept of developing miniaturized in-vivo robotic instruments with the state-of-the-art technology and endoscopic navigation has become compelling in recent decades [10]. SPRINT, a 6-dof robotic system, has four in-vivo motors and a shoulder joint operating outside the human body [2]. It consists of two robotic arms (diameter 18 mm). The system is inserted in the abdominal cavity through a cannula of 34 mm diameter. Due to limited in-vivo dof, it is not possible for the surgeon to re-position the robotic arms once they are inserted. In a system designed by Wortman et al., a pair of in-vivo actuated 7-dof robotic arms (diameter 26 mm) has a feature of repositioning by increasing their default incision size (30 mm) [11]. With a smaller incision size requirement, systems possessing snake-like robotic arms are designed to work in a confined workspace, however, torque availability is comparatively less [12,13].

The major challenges in single-port surgical systems' design process are to reduce the incision size, enough torque availability at the end-effector and possibility of arms re-positioning without increasing the incision size. In this work, a new design of fully in-vivo actuated 7-dof robotic arm and its integration with cannula-swivel system are presented. The integration of whole robotic platform provides the possible solution to the challenges discussed above.

2. System design and prototype

The proposed system consists of two serial arms sequentially inserted parallel to the axis of cannula, as shown in figure 1. The diameter and length of the arms is 15.8 mm and 200 mm, respectively. The cannula is a hollow tube with an outer diameter of 20 mm and an inner diameter of 16 mm. It is used as an access port into the abdominal cavity. The robotic arms are deployed to the working position by the embedded motors inside the arms and are securely anchored to the flaps of the cannula by lock pins [14].

The external swivel system (shown in figure 1) can adjust the insertion of the cannula to re-position the robotic arms even when arms are deployed inside the abdominal cavity. This system has three independent dof for telescopic, yaw and pitch adjustments of the cannula. The centre of rotation of the pitch is at the point of insertion to avoid an increase in incision size while re-positioning of the arms. These motor-actuated movements are not considered as additional dofs of the system.

2.1 Robotic arms and master console

The serial arm designed for this project has 7-dof and the Denavit-Hartenberg (D-H) conventions are utilized to attach the co-ordinate frame to each joint as shown in figure 2 [15]. For the first 6-dof of the robotic arm, seven frames are attached to compute six transformation matrices. The 7th dof is for the movement of end effector such as for grasping, cutting etc., therefore, it is not included in the forward kinematics computations. Each matrix establishes a relation between ith and i-1th frame.
**Figure 1.** Prototype of the surgical robotic system showing the robotic arms that have been inserted through the cannula and anchored to the external swivel system.

**Figure 2.** Robotic arm configuration.

| Link no. | Link length ($a_i$) | Twist angle ($\alpha_i$) | Joint offset ($d_i$) | Joint angle ($\theta_i$) |
|----------|---------------------|--------------------------|---------------------|--------------------------|
| 1        | 0                   | 0                        | 0                   | $-\frac{\pi}{4} \leq \theta_1 \leq \frac{\pi}{4}$ |
| 2        | 0                   | $\frac{\pi}{2}$          | 0                   | $0 \leq \theta_2 \leq \frac{\pi}{2}$ |
| 3        | $a_2$               | 0                        | 0                   | $0 \leq \theta_3 \leq \frac{7\pi}{12}$ |
| 4        | 0                   | $-\frac{\pi}{2}$        | $d_4$               | $0 \leq \theta_4 \leq \pi$ |
| 5        | 0                   | $\frac{\pi}{2}$         | 0                   | $-\frac{\pi}{2} \leq \theta_5 \leq \frac{\pi}{2}$ |
| 6        | $a_5$               | $-\frac{\pi}{2}$        | 0                   | $-\frac{\pi}{2} \leq \theta_6 \leq \frac{\pi}{2}$ |

The kinematic equations for the end effector are computed using the homogeneous transformation matrix for the D-H parameters given in table 1. All the joints in the system are revolute, therefore, only joint angles ($\theta_i$) are variables and all the other D-H parameters i.e. link twist ($\alpha_i$), link length ($a_i$) and joint offset ($d_i$) are fixed. Utilizing D-H parameters given in the table 1, end-effector’s position vector can be computed as,

\[
p_x = a_2c_2c_3 - a_3(c_3s_2s_4 - c_1c_2c_3c_4) + s_3(c_1c_2s_3 - c_3s_1 + c_1c_3s_2) - d_4(-c_1c_2s_3 - c_1s_2c_3),
\]

\[
p_y = a_5(c_3s_4 + c_2c_3s_4) - s_5(c_1c_3 + c_2s_1s_3 + c_3s_1s_2) - d_4(-s_1c_2s_3 - s_1s_2c_3) + a_2s_1s_2,
\]

\[
p_z = d_4(-s_2s_3 + c_2c_3) + a_2s_2 + a_5(s_5(c_2c_3 - s_2s_3) + c_3c_4c_2s_2),
\]
where, \( p_x, p_y \), and \( p_z \) are the position vectors of the end effector in x, y and z direction, respectively. The \( C \) and \( S \) are abbreviation used for cosine and sine functions whereas 1, 2,...,5 in the subscript of the \( C \) and \( S \) are \( \theta_1, \theta_2, ..., \theta_5 \), respectively.

In the proposed system, a pair of 7-dof robotic arms are tele-operated with the help of two master manipulators. The first 3-dof of master manipulators are responsible for the 3-axis translational movements of corresponding first three joints of the robotic arm. The end-effector movements are controlled by the surgeon's fingers. A foot pedal is provided for re-positioning of the master manipulators to retain the surgeon's working posture. This foot pedal is used to disengage the control and to lock the robotic arms at the concurrent posture. After adjusting the working posture of the master manipulator, clutch is engaged to control the arms at the locked posture.

3. Results and Discussions

Forces and the workspace related measurements are presented in table 2. The maximum measured gripping force (20 N) is comparable to the force reported using the da Vinci Si system [16]. The arms can lift a load of 500 g when the total stretched length (shortest distance measured from first joint to end-effector) is 112.3 mm. The shared work volume of this system (shown in figure 3) is also appropriate as compared to the requirements reported for various robot assisted surgical tasks by Hwang et al. [17]. Shared workspace refers to the operative space where both robotic arms can reach. Currently, the distance between the first actuated joint of the robotic arm from the cannula centre is 103 mm (shown in figure 2) which is required for better triangulation. This distance can be decreased to enhance the shared workspace but at the expense of triangulation. In a single-port system, there is a trade-off between shared workspace and triangulation of the arms.

The proposed overall system design requires a small incision (for the insertion of 20 mm diameter cannula), possesses multi-quadrant access and occupies a small footprint in the operating room. The robotic arms can be re-positioned using the cannula-swivel system combination. The swivel system gives the flexibility of re-positioning of the arms without increasing the size of incision. With this feature, it can allow multi-quadrant access for the surgeon through a single-port approach. Furthermore, there is a requirement of an extra dof to achieve remote centre-of-motion (RCM) in some of the reported systems which is not required in the current design due to all in-vivo actuated joints of robotic arms.

Figure 3. Shared workspace representation of both the robotic arms.
Table 2. Force, power and workspace measurements

| Attribute            | Measurement          |
|----------------------|----------------------|
| Gripping force       | 20 N                 |
| Payload-lifting      | 500 g                |
| Output power         | 469 mW               |
| Total workspace      | 252 mm × 192 mm × 322 mm |
| Shared workspace     | 205 mm × 77 mm × 64 mm |

Surgical tasks in laparoscopic surgery, such as, intracorporeal suturing and knot-tying that require high dexterity of the robotic arms, were used to validate the system’s performance. Precise movements of all the joints and the end-effector are required to conduct these tasks. Using the C loop technique, the robotic arms demonstrated its ability to tie a knot. As shown in figure 4a, the knot was tied by the two arms pulling in the opposite direction. The feasibility of the robotic arms, in terms of design objectives, was also evaluated in a non-survival porcine model. The animal procedures were performed at the Surgical Skill Centre of The Hong Kong University with experimental protocols approved by the Committee on the Use of Living Animals in Teaching and Research. The robotic arms were fitted with a grasper and a cautery hook that enabled the surgeon to grasp, manipulate and cauterize living tissues. The gall bladder was successfully removed by electrocautery using the robotic arms. Figure 4b shows a view of robotic arms during a technically challenging cholecystectomy procedure. The results have demonstrated that the proposed robotic arm design is able to perform basic surgical tasks required for an abdominal surgery.

![Image of robotic arms](image)

Figure 4. Surgical tasks (a) Knot tying task (b) Gall bladder removal.

4. Conclusion

The aim of the current work is to present the design and to evaluate a totally in-vivo actuated miniature surgical robot platform for abdominal surgeries. The proposed system is compact (due to fully in-vivo actuation), able to re-position without increasing the incision size and has sufficient torque to perform various surgical tasks inside the abdomen. Results have shown that the robot arm can accomplish the desired surgical tasks with high dexterity. In future work, optimal dimensional analysis is required to enhance the shared workspace.
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