Incision Port Displacement Modelling Verification in Minimally Invasive Surgical Robots

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INTRODUCTION

Robot-assisted minimally invasive surgical procedures are long and complex involving large expert teams that perform a plethora of tasks required for the successful completion of surgery. Since the mid-80s, robotic assistance involved a surgeon to teleoperate surgical tools providing no automation or autonomy in its performance. Enabling surgical robots for automation could provide more precision and speed while obviating the need for long surgical training to carry out unwieldy tasks. This paper considers one aspect of using robotic instruments to autonomously perform precision motion in robot-assisted laparoscopic surgery where robotic instruments go through trocars inserted through the patient's skin. The experience shows that the elasticity of the skin causes displacements of the incision ports which can result in localization and motion errors, thus, creating inaccuracy in robot performance by moving the instrument in undesirable directions. The offline calibration that calculates exact kinematic parameters does not account for online errors due to interactions with the unstructured environment [1]. Some approaches use force sensors in the trocar or in the robot to minimize interactions at the port or passive joints between the instrument and the robot end-effector to assess more accurately the instrument pose [2, 3]. Another way to approach the issue is by measuring the position of the instrument tip using cameras or magnetic position trackers. Such measurements eliminate the problem of errors in the forward kinematics, but do not directly solve the problem of errors in the inverse kinematics and position control. In [4], authors present online estimation of the local Jacobian using position information to reduce the effects of errors in inverse kinematics. However, this approach is sensitive to significant motion in a single direction.

In order to analyse the aforementioned error at the incision port, this research study aims at modelling incision port displacements and the instrument as a single link manipulator attached to a flexible joint. Our first objective is to experimentally emulate the surgical instrument motion through a surgical trocar inserted in artificial skin in order to highlight kinematic error induced by the elasticity of the skin.

MATERIALS AND METHODS

The experiments were conducted using the setup shown in Figure 1. A DaVinci surgical instrument was attached to the flange of a KUKA LBR iiwa robotic arm and passed through a trocar inserted in the incision port of the artificial skin. The experiments were carried out considering the incision port as a fulcrum point, i.e. the arm was controlled to rotate the instrument shaft around the incision port in a single direction by an angle of 10^o. The experiments were performed for 7 different lengths of the shaft below the skin surface $l = [13\ 15\ 17\ 19\ 21\ 23\ 25]$ *cm*, three times for each length. In order to determine induced kinematic errors, optical reflective markers were placed on the endpoint of the tool and on the incision port to track their positions using a Polaris (NDI) sensor.

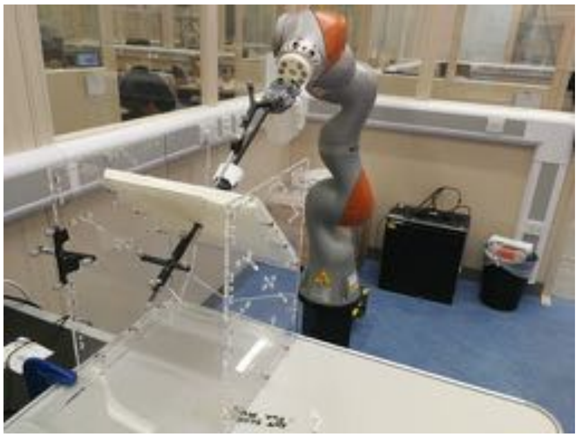

Figure 1: Experimental setup at Bristol Robotics Laboratory

RESULTS

Figure 2 shows the tool (blue lines) and the incision port (red lines) endpoints in the Cartesian space for one of the experiments where the instrument shaft was 19 *cm* below the skin. The initial pose of the shaft is denoted by grey lines while the pose of the shaft at the end of the motion is denoted by black lines. The arrows show the motion direction of the tool endpoint. The solid lines correspond to the positions calculated using forward kinematics whereas the dashed lines correspond to the positions measured by the Polaris sensor. The significant error between the positions renders the incision port non-rigid (detail in Figure 2). Figure 3 shows the Euclidean norm of the position errors of the tool endpoint and the incision port with respect to the different lengths of the shaft beneath the skin. The bars represent the minimum and maximum error values recorded in the experiments. For a single experiment, Table 1 shows statistical features of the incision port position displacements when the instrument's length is 13 *cm* below the skin.

MATHEMATICAL MODEL

In this section, we present a fundamental model, a single-link manipulator with a flexible joint, to define the error of the end-effector position induced by the incision port displacement. The schematic view of the flexible joint manipulator is depicted in Figure 4. It is clear that the system has two de-

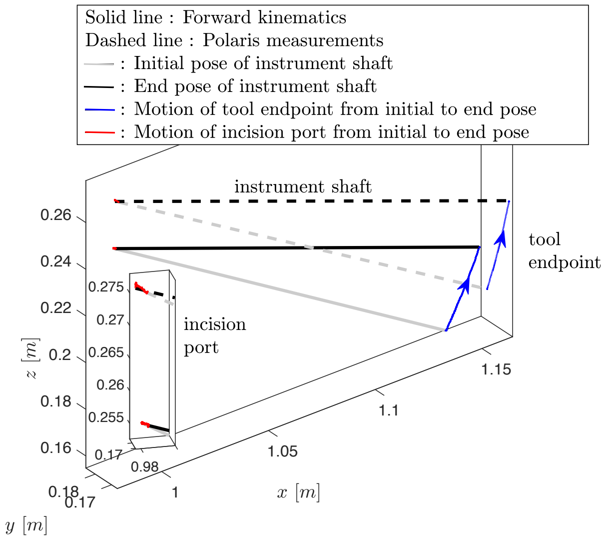

Figure 2: Motion of tool endpoint and incision port in the Cartesian space. Comparison between positions calculated using forward kinematics and positions measured by Polaris. (Experiment time: 5 seconds)

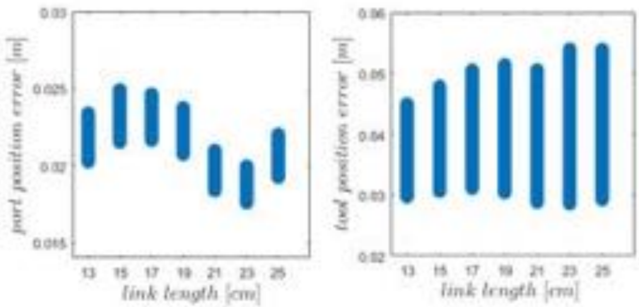

Figure 3: Min-max values of the Euclidean norm of position errors with respect to the shaft length that is below the skin (*Left:* incision port. *Right:* tool endpoint)

Error Statistics [cm]	
Mean	2.19
Minimum	2.06
Maximum	2.31
Mode	2.06
Standard Deviation	0.000733

Table 1: Error statistics

grees of freedom corresponding to the rotation of the motor shaft with respect to a coordinate frame fixed to the base, and the rotation of the flexible joint with respect to the motor. The generalized coordinates are therefore the angular position of the motor θ_m and the angular displacement of the flexible joint θ_j (see Figure 4). The state-space representation of the system is:

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \frac{k_s}{J_m}(x_3 - x_1) + \frac{1}{J_m}\tau \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= \frac{-k_s}{J_l}(x_3 - x_1) + \frac{mgl}{2J_l} sinx_3
\end{aligned} \tag{1}$$

where $[x_1, x_2, x_3, x_4] = \left[\theta_m, \dot{\theta}_m, \theta_l, \dot{\theta}_l\right]$ is the state vector, τ is motor torque, l and m are length and mass of the link, respectively. In order to validate the proposed model, experimental

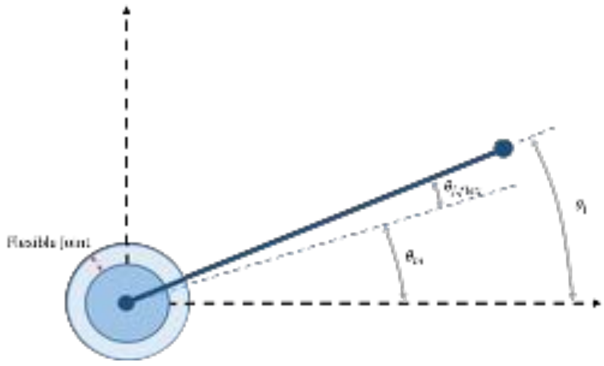

Figure 4: Flexible Joint

tests are needed where all inherent system parameters, such as the motor moment of inertia J_m and spring stiffness k_s, can be calculated. However, experimental model validation is an extension of the current study.

CONCLUSION AND DISCUSSION

According to Figure 3, it is clear that there is a significant error in the position of the incision port (an average of 2 *cm*) which in turn induces a larger error in the position of the tool endpoint (an average of 4 *cm*). The larger error in the tool position might also be a consequence of the instrument shaft's inherent flexibility. Noise and other factors can also affect the accuracy of the sensor's measurements, which according to the manufacturer is 0.35 mm RMS. Nevertheless, these error values can be critical in some MIS applications where much higher precision would be required (e.g. cardio-vascular or ENT surgery). Consequently, a model that incorporates these displacements is needed for accurate position control. This displacement at the incision port can be modelled as a single link flexible-joint planar manipulator as depicted in Figure 4, where flexible joint motion represents the undesired incision port motion.

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