Perception, control and path planning of robotic laparoscopic surgical system

Alexios Karadimos

Deparment of Electrical and Computer Engineering

Patras, February 2022

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ
UNIVERSITY OF PATRAS

Table of Contents

Outline

Surgical Robotics Procedure

Advantages & Disadvantages of Surgical robotics

Biblography overview

Thesis goals

Outline

Forward Kinematics

Singularity points

RCM constraint

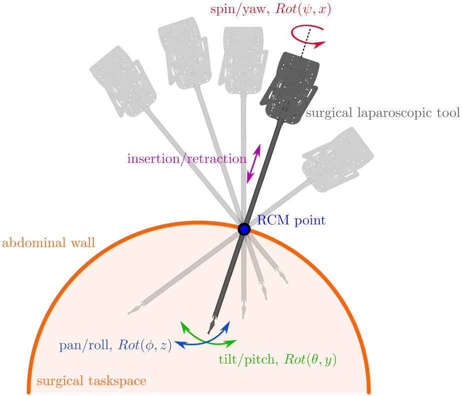


Figure: Illustration of pivoting motion of surgical laparoscopic tool around RCM point (also known as fulcrum or trocar point). Due to the RCM constraint, the tool has only 4 degrees of freedom.

Elbow-up constraint

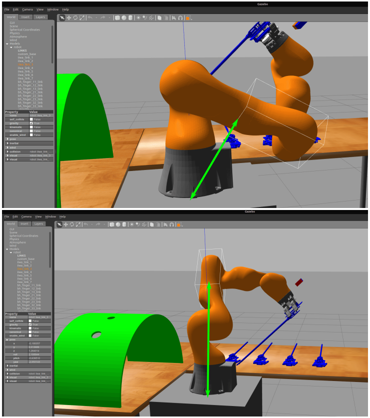
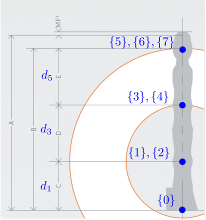


Figure: Top: elbow-down solution, bottom: elbow-up solution



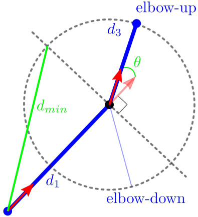


Figure: Elbow-up constraint description with relative distance or angle between links with lengths d_1 and d_3

$$d_{\text{min}} \leq d \leq d_{\text{max}}, \text{ where}$$
$$d_{\text{min}} = \sqrt{d_1^2 + d_3^2} = 553\text{mm and}$$
$$d_{\text{max}} = d_1 + d_3 = 780\text{mm}.$$

Outline

Gripper & Forward Kinematics

Gripper Inverse Kinematics

Outline

Laparoscopic tool detection

Calculation of tool position and orientation

Calculation of grasping points

Outline

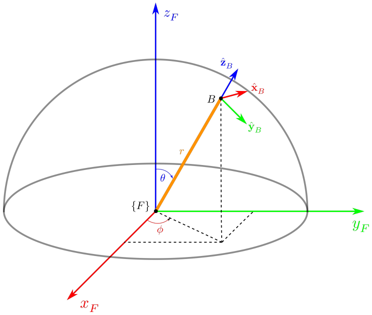
Path Planning - Sampling methods

Pick and place algorithm

Task space analysis

Outline

Tool pose



$$ {}^{F}T_B = \begin{bmatrix} {}^{F}R_B & {}^{F}\mathbf{p}_B \\ \mathbf{0} & 1 \end{bmatrix} $$

where

$$ {}^{F}R_B = \begin{bmatrix} \hat{\mathbf{x}}_B & \hat{\mathbf{y}}_B & \hat{\mathbf{z}}_B \end{bmatrix} $$

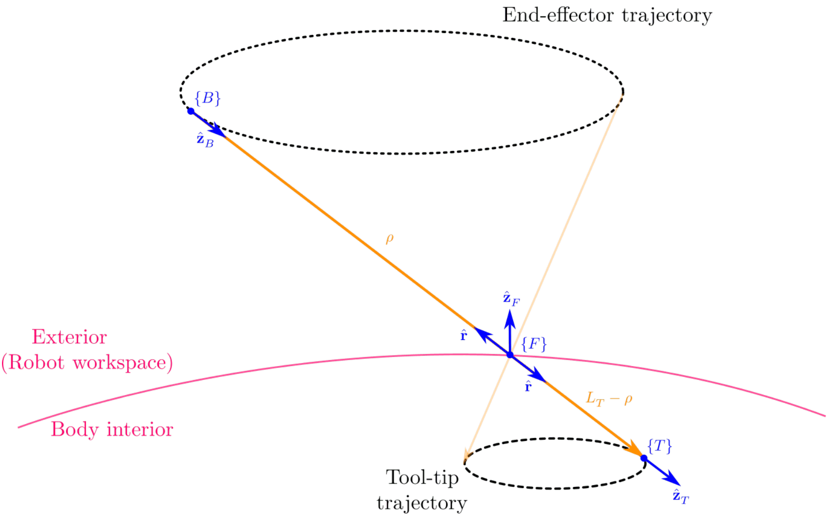
Calculate orientation vectors using spherical coordinate unit vectors

$$ \hat{\mathbf{x}}_B = \hat{\phi} = \begin{bmatrix} -\sin(\varphi) \\ \cos(\varphi) \\ 0 \end{bmatrix} $$

$$ \hat{\mathbf{y}}_B = \hat{\theta} = \begin{bmatrix} \cos(\theta)\cos(\varphi) \\ \cos(\theta)\sin(\varphi) \\ -\sin(\theta) \end{bmatrix} $$

$$ \hat{\mathbf{z}}_B = \hat{\mathbf{r}} = \begin{bmatrix} \sin(\theta)\cos(\varphi) \\ \sin(\theta)\sin(\varphi) \\ \cos(\theta) \end{bmatrix} $$

The Fulcrum Effect



Line segment trajectory of tool tip

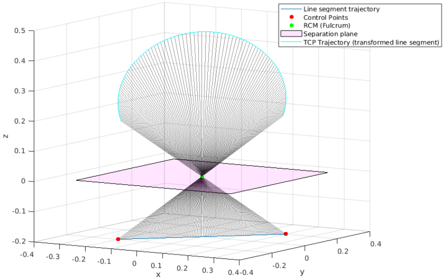
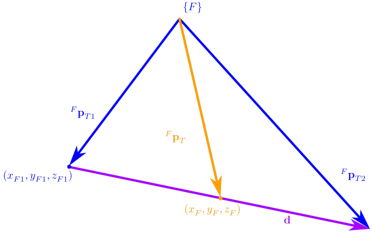


Figure: A Line segment trajectory and it's transformation due to the Fulcrum Effect



$$\begin{cases} x_F = (1-s)x_{F1} + s x_{F2} \\ y_F = (1-s)y_{F1} + s y_{F2} \\ z_F = (1-s)z_{F1} + s z_{F2} \end{cases}$$

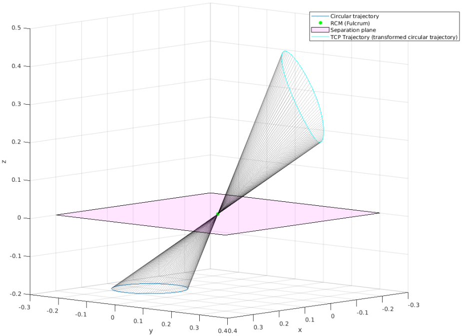


Figure: Circular trajectory of tool tip with respect to Fulcrum reference frame and it's transformation via the Fulcrum Effect

$$\begin{cases} x_F = r_0 \cos(2\pi s) + x_{F0} \\ y_F = r_0 \sin(2\pi s) + y_{F0} \\ z_F = z_{F0} \end{cases},$$

$$s \in [0, 1]$$

$$\begin{cases} r = \sqrt{x_F^2 + y_F^2 + z_F^2} \\ \theta = atan2\left(\sqrt{x_F^2 + y_F^2}, z_F\right) \\ \varphi = atan2(y_F, x_F) \end{cases}$$

Circular trajectory of tool tip

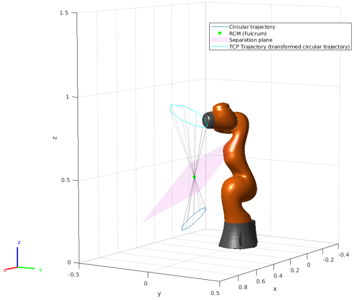


Figure: Circular trajectory that lies on an a plane of arbitrary orientation with respect to the fulcrum point

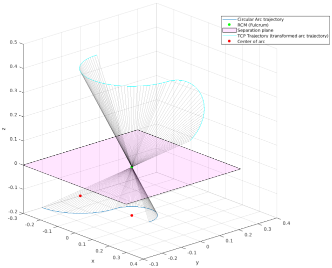


Figure: Circular arc trajectory of tool tip with respect to Fulcrum reference frame and it's transformation via the Fulcrum Effect. In this trajectory 2 circular arcs are used

Cubic Spline trajectory of tool tip

B-Spline trajectory of tool tip

Polynomials of 5th order

Planning with velocity profiles

Outline

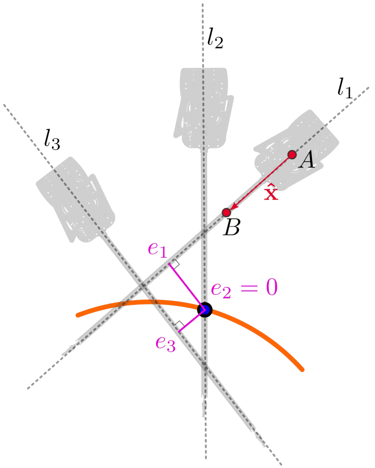


Figure: Geometric calculation of the RCM alignment error e using the distance between the line l and the RCM point.

$$^{U}T_{T0} = \begin{bmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} & \mathbf{p} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\overrightarrow{O_F A} = \mathbf{p}, \quad \text{and} \quad \overrightarrow{O_F B} = \mathbf{p} + \hat{\mathbf{x}}$$

$$e_{rcm} = d(l, O_F)$$

$$d(l, O_F) = \frac{\|\overrightarrow{O_F A} \times \hat{\mathbf{x}}\|}{\|\hat{\mathbf{x}}\|}$$

RCM Tracking

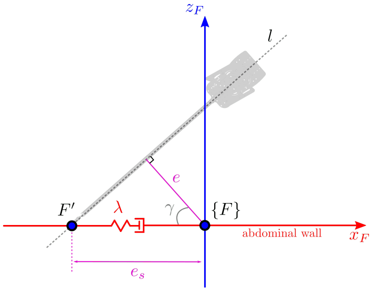


Figure: Force interaction model of the laparoscopic tool and the abdominal wall around the fulcrum point (RCM point)

$$\|\mathbf{f}_s\| = \frac{\lambda}{cos\gamma} e$$

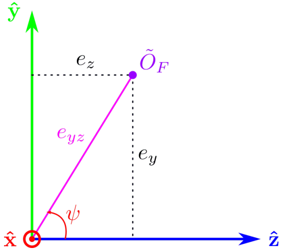


Figure: RCM error calculation in yz plane. The RCM error or yz-error is the distance between the line of the $\hat{\mathbf{x}}$ vector (here seen as a point) and the estimated position of the origin of the fulcrum reference frame $\tilde{O}_F$

RCM Tracking

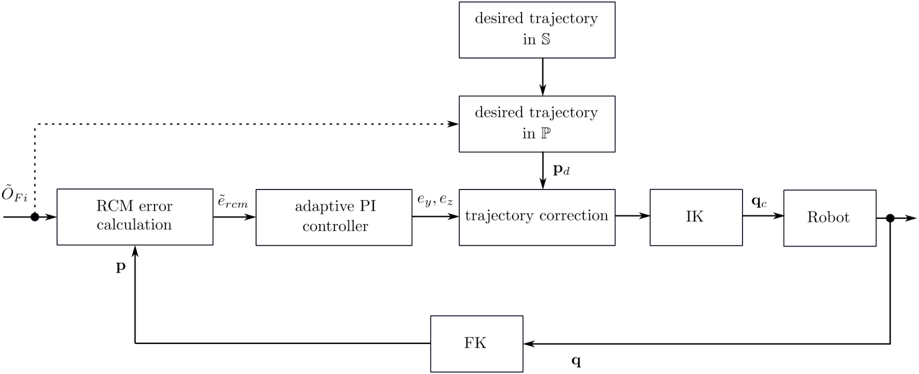


Figure: RCM tracking proposed control system. The RCM error is used as input in the trajectory generator to correct the trajectory command in order to fix the RCM misalignment

Image based visual servoing

Image based visual servoing

Outline

Introduction to the ROS framework

Gazebo simulation environment

Visualization with RViz

Motion Planning with Moveit

Tools, Packages and Libraries

Outline

Robot Planner 1: Simple MoveIt planning

Robot Planner 2: Simulation layout and reachability experiments

Robot Planner 3a: Circular and Circular arc trajectories in task space

Robot Planner 3b: Line segment trajectories in task space

Robot Planner 3c: Cubic Spline trajectories in task spac

Robot Planner 3d: B-Spline trajectories in task space

Robot Planner 3e: Polynomial trajectories in joint space

Robot Planner 3f: Trajectories in joint space with trapezoidal velocity profile

Robot Planner 3g: Trajectories in joint space with s-curve velocity profile

Robot Planner 4: Simple cube pick-and-place experiment

Robot Planner 5: Visual servoing

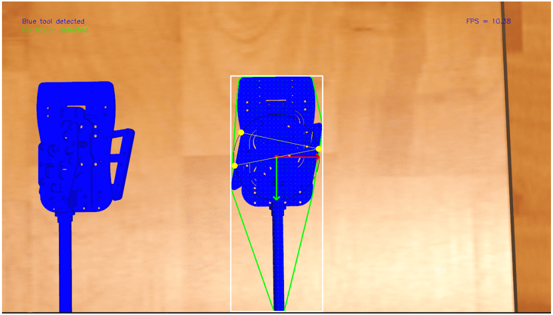


Figure: Image based visual servoing and calculation of grasp points. The yellow points are the grasp points and the thin black circumscribed circle is the growing circle that was used to calculate them.

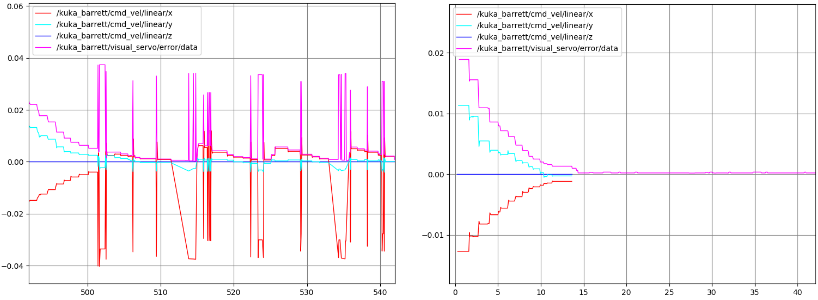
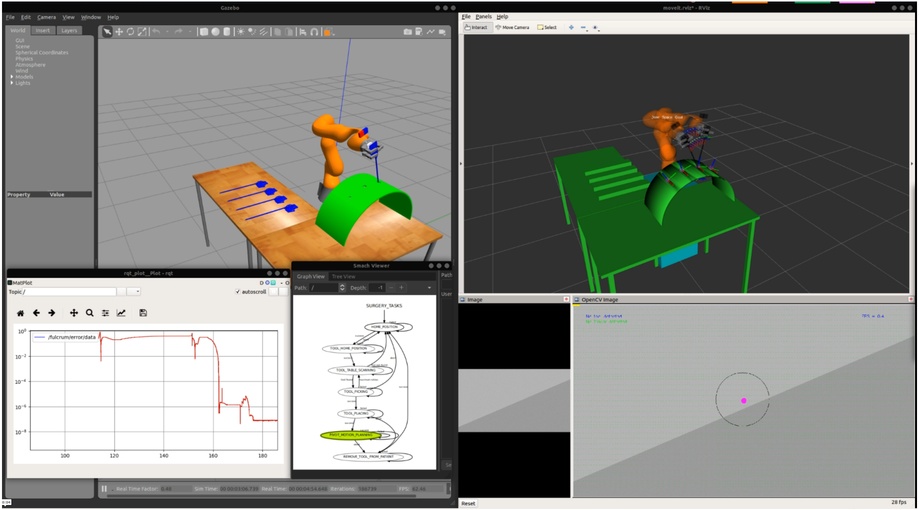


Figure: Visual servo controller error diagrams. On the left image in the error graphs appear some spikes. These spikes occur from the sudden temporary detection of a nearby surgical tool. On the right image, these spikes are filtered out, and only the error graphs of the visual servoing of one tool are shown. The controller parameters are $K_p = 0.9, K_d = 0.2$

Demo



https://youtu.be/lfV1vdHf7bk

Outline

Conclusions & Comparison with similar projects

Future Work