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

Inverse Kinematics - Decoupling Technique

Singularity points

RCM constraint

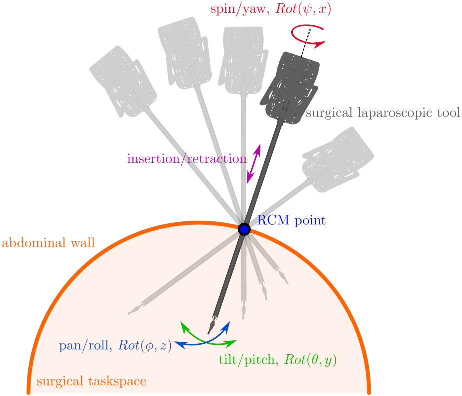


Figure: Illustration of pivoting motion of surgical laparoscopic tool around RCM point (also known as fulcrum or trocar point). Due to the RCM constraint, the tool has only 4 degrees of freedom.

Elbow-up constraint

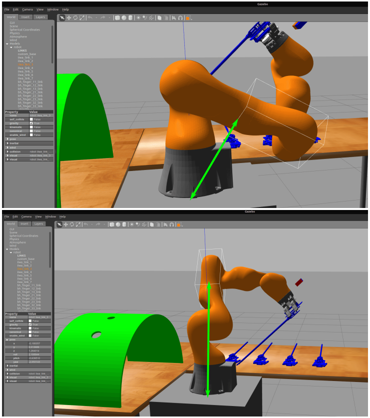


Figure: Top: elbow-down solution, bottom: elbow-up solution

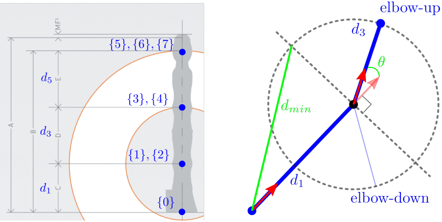


Figure: Elbow-up constraint description with relative distance or angle between links with lengths d_1 and d_3

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

Outline

Gripper & Forward Kinematics

Gripper Inverse Kinematics

Outline

Laparoscopic tool detection

Calculation of tool position and orientation

Calculation of grasping points

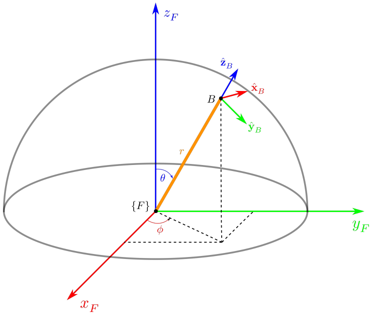
Outline

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

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

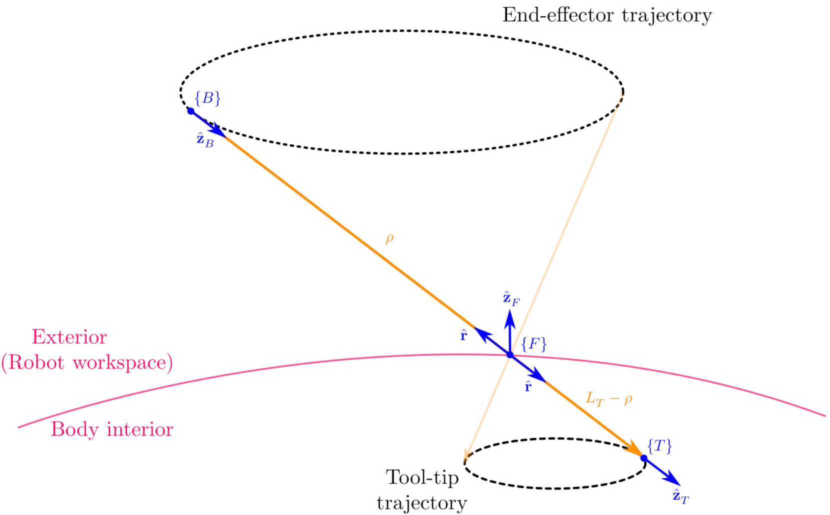
Calculate orientation vectors using spherical coordinate unit vectors

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

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

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

The Fulcrum Effect



Line segment trajectory of tool tip

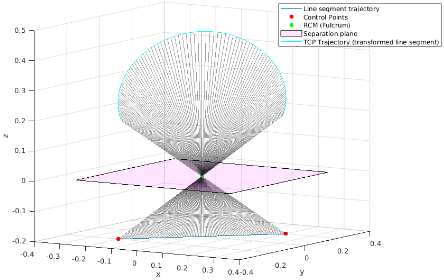
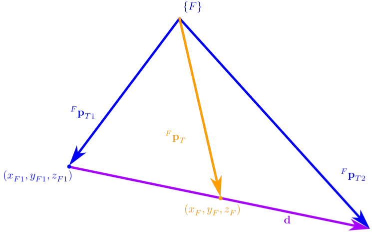


Figure: A Line segment trajectory and it's transformation due to the Fulcrum Effect



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

Circular trajectory of tool tip

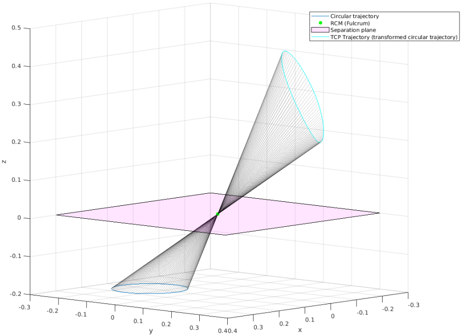


Figure: Circular trajectory of tool tip with respect to Fulcrum reference frame and it's transformation via the Fulcrum Effect

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

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

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

Circular trajectory of tool tip

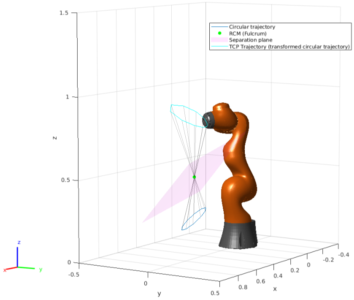


Figure: Circular trajectory that lies on an a plane of arbitrary orientation with respect to the fulcrum point

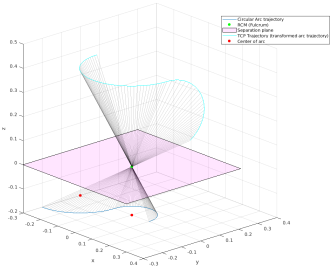


Figure: Circular arc trajectory of tool tip with respect to Fulcrum reference frame and it's transformation via the Fulcrum Effect. In this trajectory 2 circular arcs are used

Cubic Spline trajectory of tool tip

B-Spline trajectory of tool tip

Polynomials of 5th order

Planning with velocity profiles

Outline

RCM Tracking

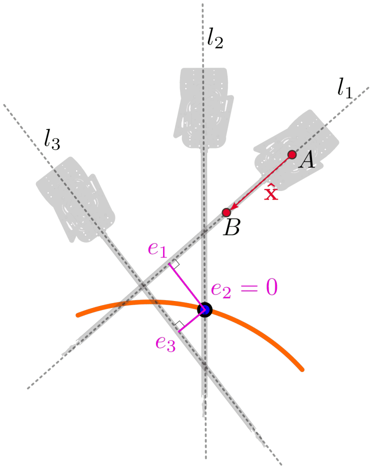


Figure: Geometric calculation of the RCM alignment error e using the distance between the line l and the RCM point.

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

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

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

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

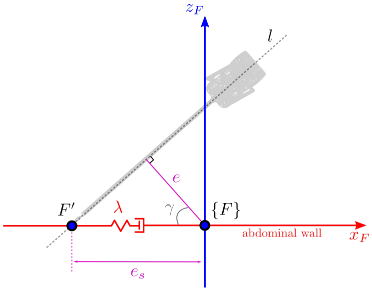


Figure: Force interaction model of the laparoscopic tool and the abdominal wall around the fulcrum point (RCM point)

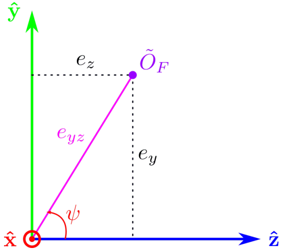


Figure: RCM error calculation in yz plane. The RCM error or yz-error is the distance between the line of the $\hat{\mathbf{x}}$ vector (here seen as a point) and the estimated position of the origin of the fulcrum reference frame $\tilde{O}_F$

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

RCM Tracking

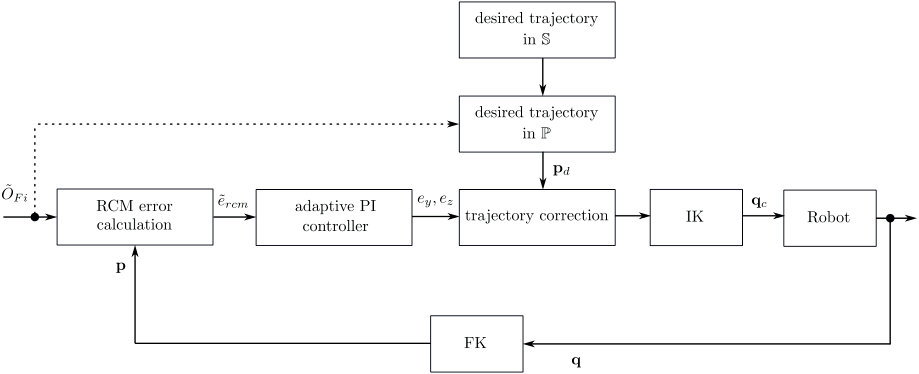


Figure: RCM tracking proposed control system. The RCM error is used as input in the trajectory generator to correct the trajectory command in order to fix the RCM misalignment

Image based visual servoing

Figure: Image based visual servoing. The robot arm is controlled using the information gained from the video frames. The frames are 2-Dimensional and thus the detected objects can have only 3 degrees of freedom which means we can mainly control 3 independent variables, here the x, y, θ variables. The left image is the initial frame and the right image is the frame where the object is at the target pose.

$$\mathbf{e}[kT] = [e_x, e_y, e_\theta]^\top$$

Image based visual servoing

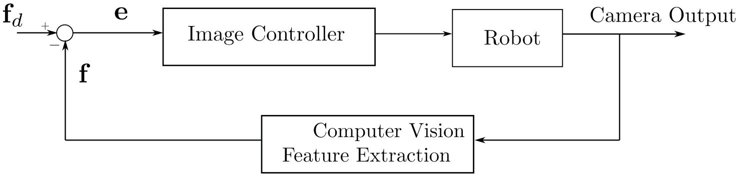


Figure: Image based visual servoing closed loop control

$$\mathbf{x}[k+1] = \mathbf{x}[k] + \mathbf{u}[k]$$

$$\mathbf{u}[k] = K_p \mathbf{e}[k] + K_i \sum_{i=0}^{k-1} \mathbf{e}[iT] + K_d \left(\mathbf{e}[kT] - \mathbf{e}[(k-1)T]\right)$$

Firm grasping algorithm & Force control

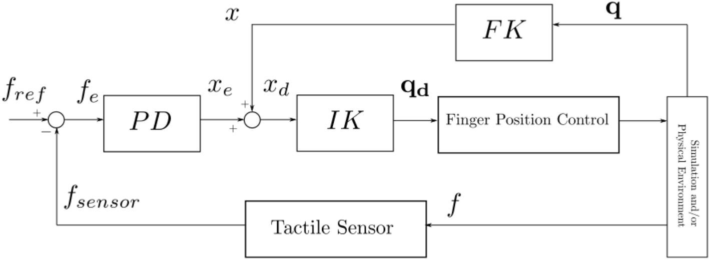


Figure: Force control on a Barrett Hand gripper finger

Outline

ROS framework

Key components:

- Nodes
- Topics & Messages
- Parameters
- Launch files
- Packages
- ROS filesystem, network, tools & community
- and more ...

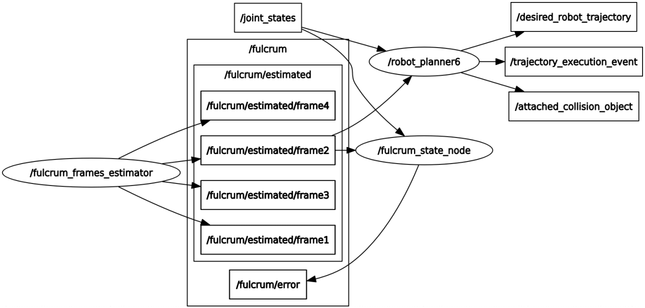


Figure: Subset of ROS nodes and topics used for the robot-planner6 experiment

Gazebo simulation environment

Visualization with RViz

Motion Planning with Moveit

Outline

Robot Planner 1: Simple MoveIt planning

Robot Planner 2: Simulation layout and reachability experiments

Robot Planner 3b: Line segment trajectories in task space

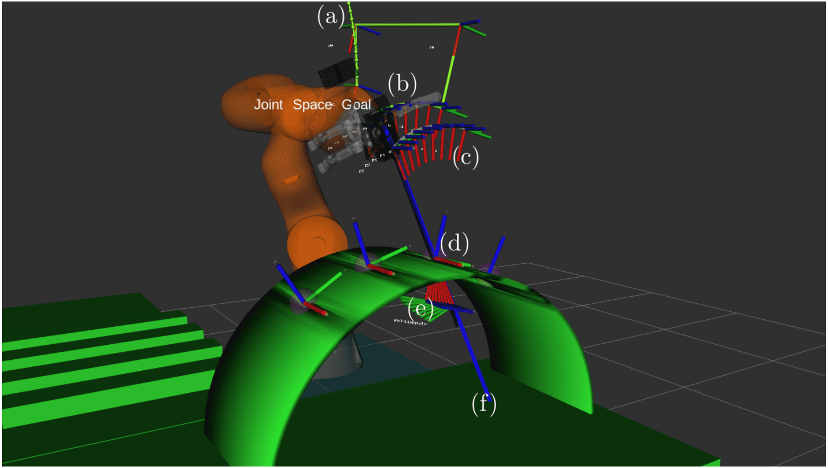


Figure: Experiment 3b

Robot Planner 3b: Line segment trajectories in task space

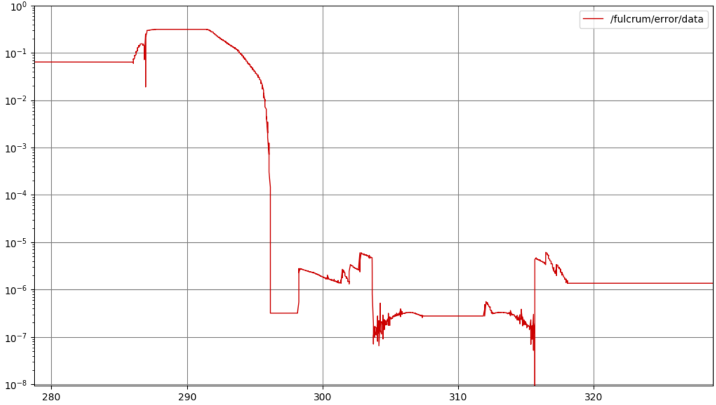


Figure: RCM error diagram from home position to line and reverse-line segment trajectories.

Robot Planner 3b: Line segment trajectories in task space

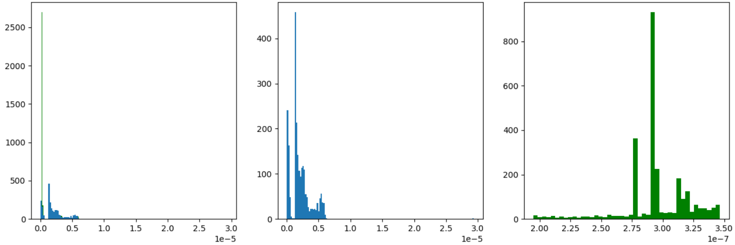


Figure: RCM error distributions, measurements from 10 iterations of the same experiment. From left to right: distribution of all measurements, distribution of measurements while the robot was pivoting, distribution of measurements while the robot was inserted but still.

	Average [m] (accuracy)	Standard Deviation [m] (repeatability)	sample size
while pivoting	$2.112649 \cdot 10^{-6}$	$1.609277 \cdot 10^{-6}$	2309
while inserted and still	$2.948652 \cdot 10^{-7}$	$2.948652 \cdot 10^{-7}$	2696

Line segment trajectories in task space

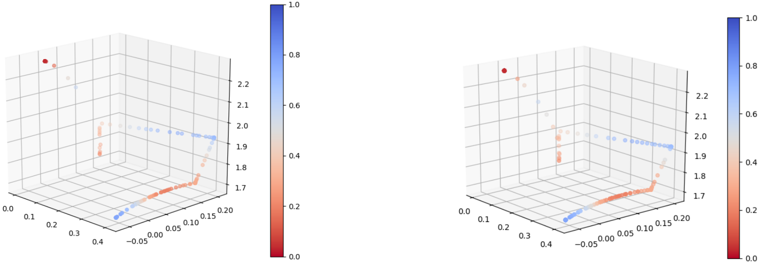


Figure: Experiment 3b: Manipulability plots of the whole trajectory the robot executed during 2 iterations of the same experiment

Robot Planner 3b: Line segment trajectories in task space

Robot Planner 3b	Approach and **line segment pivot** trajectories with **RRTConnect**			
	elbow-up preparatory path			
10 Experiments	Elbow-up Start pose planning time (sec)	Execution status	Elbow-up preparation path planning time (sec)	Execution status
Average	0.174222	1	0.117040	1
Standard deviation	0.049002	-	0.084238	-
	Approach & Insertion			
10 Experiments	Approach fulcrum 2 path planning time (sec)	Execution status	Insertion path planning time (sec)	Execution status
Average	0.116498	1	0.249556	1
Standard deviation	0.088078	-	0.078941	-
	Line segment pivot trajectories			
10 Experiments	Line segment path planning time (sec)	Execution status	Reverse line segment path planning time (sec)	Execution status
Average	1.809001	1	5.356607	0.7
Standard deviation	2.421448	-	0.086818	-

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

Robot Planner 3h: Helical trajectories in task space

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

Robot Planner 5: Visual servoing

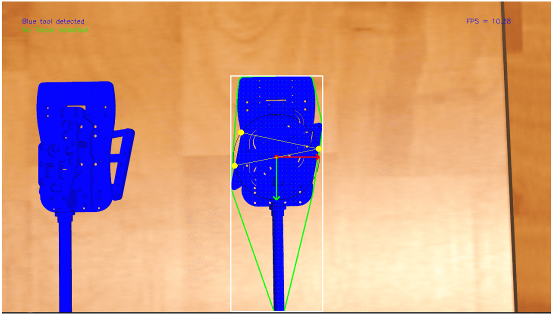


Figure: Image based visual servoing and calculation of grasp points. The yellow points are the grasp points and the thin black circumscribed circle is the growing circle that was used to calculate them.

Robot Planner 5: Visual servoing

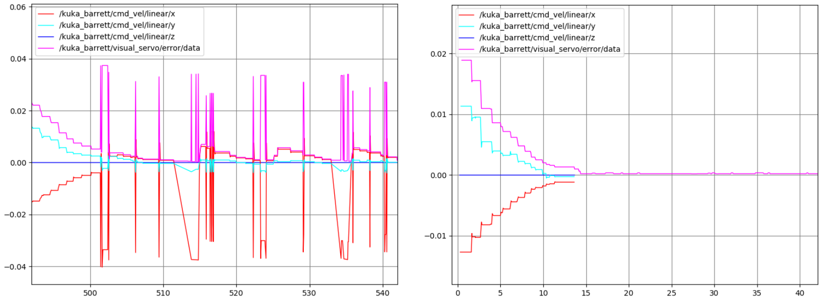
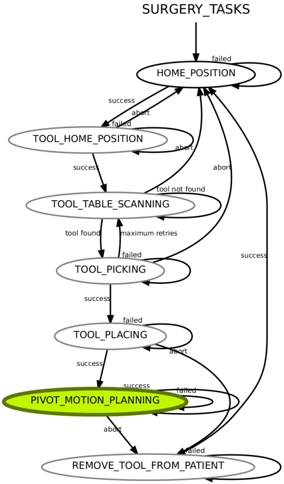


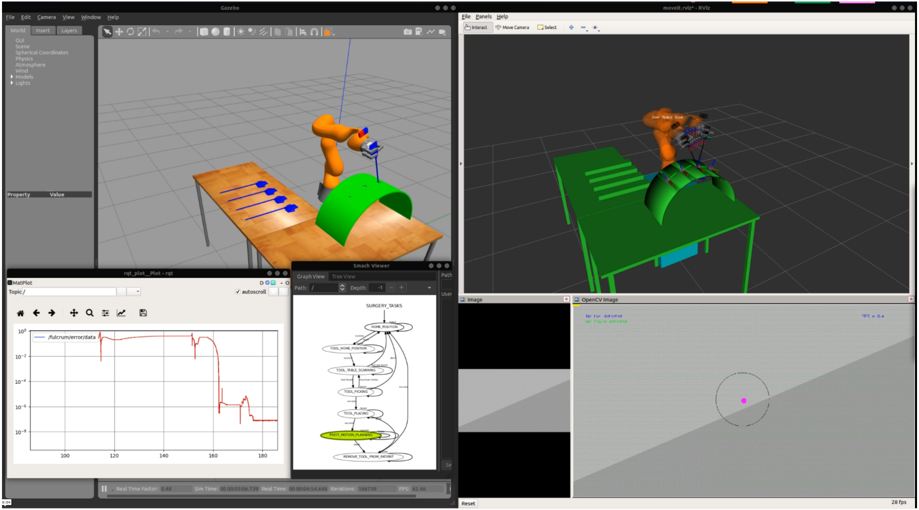
Figure: Visual servo controller error diagrams. On the left image in the error graphs appear some spikes. These spikes occur from the sudden temporary detection of a nearby surgical tool. On the right image, these spikes are filtered out, and only the error graphs of the visual servoing of one tool are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

Robot Planner 6: RCM alignment error in insertion and retraction

Robot Planner 7: State machine - End-to-end simulation



Run all the stages of this thesis together (integration testing) using a state machine.



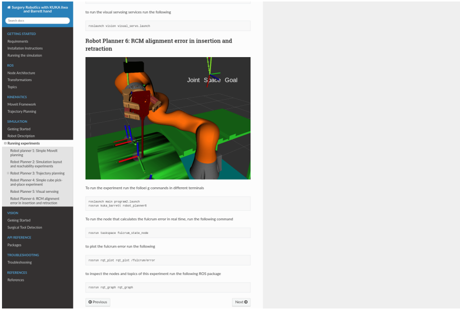
https://youtu.be/lfV1vdHf7bk

Outline

Conclusions

Future Work

Code & Documentation



- Git repository: **https://github.com/karadalex/surgery_robotics_kuka_barrett**
- Documentation: **https://karadalex.github.io/surgery_robotics_kuka_barrett/**

Questions?

Thank you,

up1046820@upnet.gr
karadalex@gmail.com