UNIVERSITY OF PATRAS - SCHOOL OF ENGINEERING
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Division: Systems and Automatic Control

Thesis

of the student of the Department of Electrical and Computer Engineering of the School of Engineering of the University of Patras

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Subject

Robotic surgical tool manipulator - Recognition, control and manipulation of laparoscopic tools

Supervisor

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ΠΙΣΤΟΠΟΙΗΣΗ

Πιστοποιείται ότι η διπλωματική εργασία με θέμα

Robotic surgical tool manipulator - Recognition, control and manipulation of laparoscopic tools

του φοιτητή του Τμήματος Ηλεκτρολόγων Μηχανικών και Τεχνολογίας Υπολογιστών

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παρουσιάστηκε δημόσια και εξετάστηκε στο τμήμα Ηλεκτρολόγων Μηχανικών και Τεχνολογίας Υπολογιστών στις

__/__/___

Ο Επιβλέπων

Ο Διευθυντής του Τομέα

Evangelos Dermatas
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Assistant Professor Dr.

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2.1 Robotic arm, DH parameters & Forward Kinematics

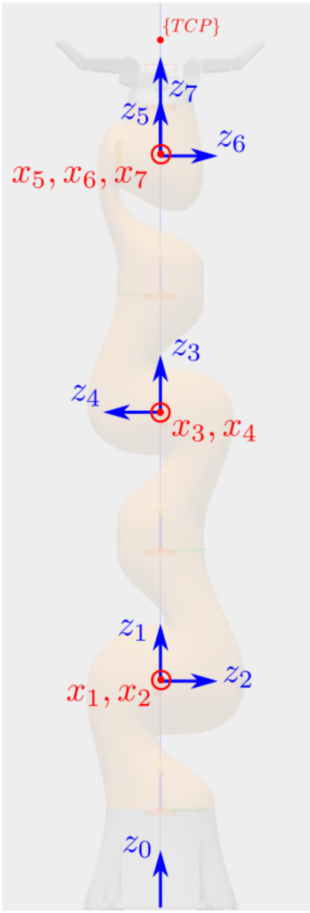


Figure 1: Joint reference frames of the KUKA iiwa14 robot

i	θ_i (rad)	L_{i-1} (m)	d_i (m)	α_{i-1} (rad)
1	θ_1	0	0.36	0
2	θ_2	0	0	$-\pi/2$
3	θ_3	0	0.36	$\pi/2$
4	θ_4	0	0	$\pi/2$
5	θ_5	0	0.4	$-\pi/2$
6	θ_6	0	0	$-\pi/2$
7	θ_7	0	0	$\pi/2$

$$^{i-1}T_i = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & L_{i-1} \\ s\theta_i ca_{i-1} & c\theta_i ca_{i-1} & -sa_{i-1} & -sa_{i-1}d_i \\ s\theta_i sa_{i-1} & c\theta_i sa_{i-1} & ca_{i-1} & ca_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

2.2 Inverse Kinematics

2.2.1 Decoupling Technique

In this section the inverse kinematics problem is solved for only the 6 out of the 7 total degrees of freedom. The third joint is not used in this analysis and it's angle is set to zero $\theta_3 = 0$. The rest of the joints form a special kind of kinematic chain that can be solved using the decoupling technique. In this technique the Inverse kinematics problem is split to 2 separate subproblems, one for the position and one for the orientation of the end-effector. This technique can be applied in this case because the axes of the 3 last joints intersect at the same point and they form an Euler wrist.

To solve for the joints' angles, the transformation matrix ${}^0T_7$ of the end-effector with respect to the robot's base is required. Usually the transformation ${}^UT_{tcp}$ is known, which is the pose of Tool's center point (TCP) with respect to the Universal Coordinate Frame $\{U\}$ from which the required ${}^0T_7$ can be calculated

$$
\begin{gathered}
{}^UT_{tcp} = {}^UT_0 \; {}^0T_7 \; {}^7T_{tcp} \\
{}^0T_7 = {}^UT_0^{-1} \; {}^UT_{tcp} \; {}^7T_{tcp}^{-1} \\
{}^0T_7 = \begin{bmatrix} R_t & \mathbf{p}_t \\ 0 & 1 \end{bmatrix}
\end{gathered}
$$

where ${}^UT_0$, ${}^7T_{tcp}$ are translation transformations by a constant distance and R_t, $\mathbf{p}_t$ are the target's orientation and position respectively.

$$
{}^0\mathbf{p}_5 = {}^0T_4 {}^4\mathbf{p}_5 = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}
$$

$$
\theta_1 = \begin{cases} atan2\left(p_y, p_x\right) \\ 2\pi - atan2\left(p_y, p_x\right) \end{cases} \tag{2.2.1}
$$

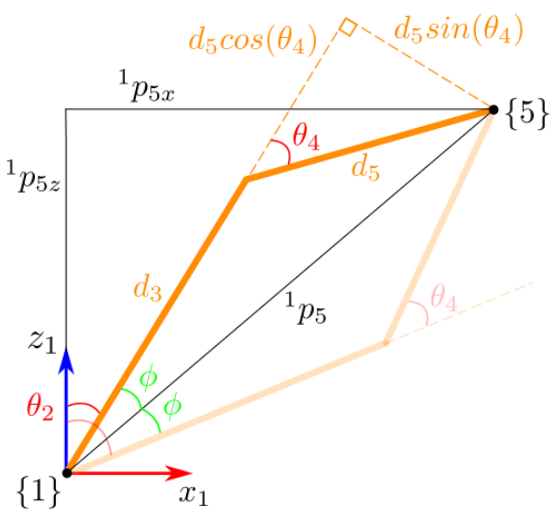


Figure 2: Calculation of angles θ_2, θ_4

$$
\varphi = acos\left(\frac{d_3^2 + \|{}^1p_5\|^2 - d_5^2}{2d_3\|{}^1p_5\|}\right)
$$

$$\theta_2 = atan2\left(\sqrt{p_x^2 + p_y^2}, {}^1p_{5z}\right) \pm \varphi \tag{2.2.2}$$

$$c_4 = \frac{\|{}^1p_5\|^2 - d_3^2 - d_5^2}{2d_3d_5}$$

$$\theta_4 = atan2\left(\pm\sqrt{1 - c_4^2}, c_4\right) \tag{2.2.3}$$

Once $\theta_1, \theta_2, \theta_3, \theta_4$ are known, the orientation matrix of the wrist can be calculated as following

$$R_{target} = \begin{bmatrix} i_x & j_x & k_x \\ i_y & j_y & k_y \\ i_z & j_z & k_z \end{bmatrix}$$

$$\theta_6 = atan2\left(\pm\sqrt{1 - k_y^2}, k_y\right) \tag{2.2.4}$$

$$\theta_7 = atan2\left(-j_y, i_y\right)$$

$$\theta_5 = atan2\left(-k_z, k_x\right)$$

2.2.2 Workspace constraints & Singularity points

2.2.3 Solutions for 7DoF numerically

2.2.4 Comparison of Inverse Kinematics Techniques

3 Grasping

3.1 Gripper & Forward Kinematics

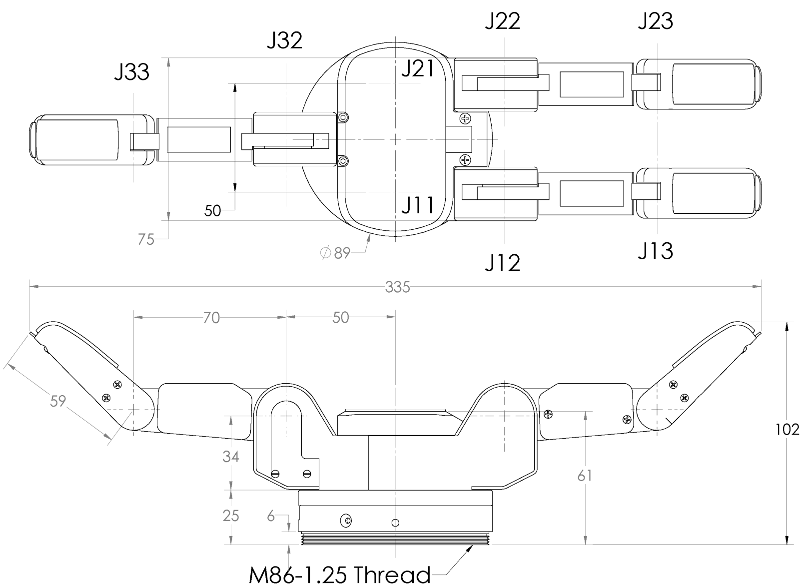


Figure 3: Barrett Hand gripper (model BH8-282) dimensions

3.2 Gripper Inverse Kinematics

The following Inverse Kinematics analysis referes to one finger of the Barrett Hand gripper, which has 3 revolute joints. Finger 3 has only 2 revolute joints for which the angle solutions are the same with the solutions of the last 2 joints of the other fingers. Let

$$\mathbf{p} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}$$

be the position of the grasp point for one finger. The first angle can easily be calculated as

$$\varphi_1 = atan2\left(p_y, p_x\right) \tag{3.2.1}$$

Next, we calculate the third angle based on the law of cosines (see fig.)

$$cos\left(\pi - \varphi_3 - \frac{\pi}{4}\right) = \frac{L_2^2 + L_3^2 - p^2}{2L_2L_3}$$

$$cos\left(\varphi_3 + \frac{\pi}{4}\right) = \frac{p^2 - L_2^2 - L_3^2}{2L_2L_3}$$

$$\varphi_3 = atan2\left[\pm\sqrt{1 - \left(\frac{p^2 - L_2^2 - L_3^2}{2L_2L_3}\right)^2}, \frac{p^2 - L_2^2 - L_3^2}{2L_2L_3}\right] - \frac{\pi}{4} \tag{3.2.2}$$

After having calculated φ_3 we can calculate φ_2

$$tan\left(\psi + \varphi_2\right) = \frac{p_z}{\sqrt{p_x^2 + p_y^2}}$$

$$tan\left(\psi\right) = \frac{L_3 sin\left(\varphi_3 + \frac{\pi}{4}\right)}{L_2 + L_3 cos\left(\varphi_3 + \frac{\pi}{4}\right)}$$

$$\varphi_2 = atan2\left(pz, \sqrt{p_x^2 + p_y^2}\right) - atan2\left[L_3 sin\left(\varphi_3 + \frac{\pi}{4}\right), L_2 + L_3 cos\left(\varphi_3 + \frac{\pi}{4}\right)\right] \tag{3.2.3}$$

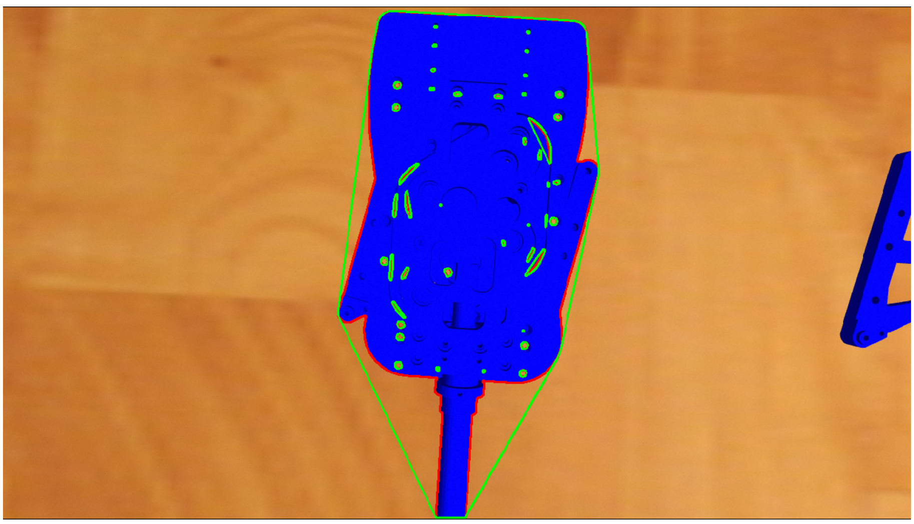
3.3 Force closure

The planar case, the spatial case & convex hull test.

3.4 Firm grasping algorithm & Force control

4 Laparoscopic tool recognition with Computer Vision

4.1 Tool detection



4.2 Calculation of grasping points

5 Laparoscopic tool manipulation

5.1 Pivoting motion with respect to Fulcrum Point

6 Path Planning

6.1 Collision avoidance

Find path points (position and orientation) by avoiding collisions

6.2 Pick and place algorithm

7 Trajectory Planning

7.1 Trajectory planning in cartesian coordinates

Connect the points from path planning with line segments and add more points if needed

7.2 Trajectory planning in joint angles space

8 Simulation with the ROS framework

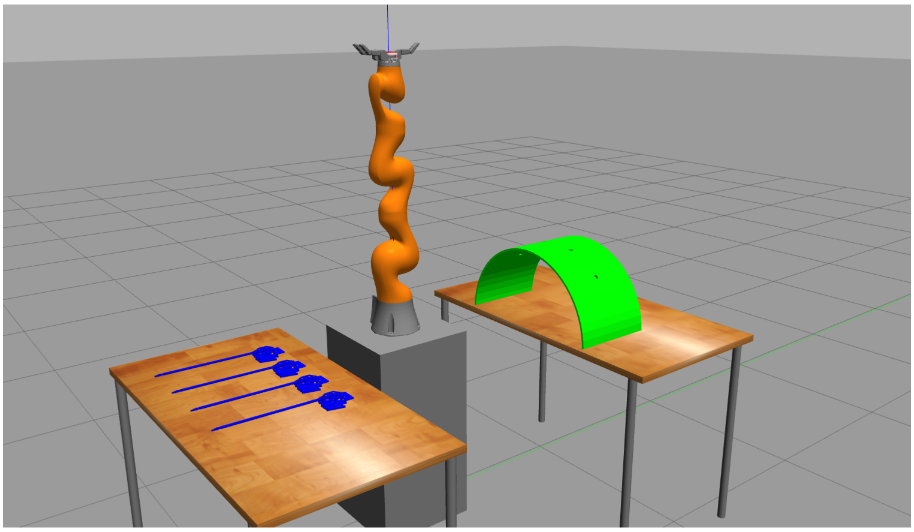


Figure 4: Simulation environment in Gazebo

Nomenclature

${}^{i-1}\mathbf{p}_{iO}$ Position vector from the origin of the coordinate frame $\{i\}$ to the origin of the coordinate frame $\{i-1\}$

${}^{i-1}R_i$ Rotation matrix from coordinate frame $\{i\}$ to coordinate frame $\{i-1\}$

${}^{i-1}T_i$ Transformation matrix from coordinate frame $\{i\}$ to coordinate frame $\{i-1\}$

c_i Shorthand notation for $cos\theta_i$

$J^{\dagger}$ Geometric Jacobian or the Pseudoinverse of the Jacobian

s_i Shorthand notation for $sin\theta_i$

List of Figures

List of programs

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