Robotics and Navigation in Medicine (Project)
Summer term 2024

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Medical Technology | Intelligent Systems

Group Project: Image Guided Robotic Needle Placement

Medical needles are widely used for minimally invasive procedures ranging from biopsies to drug insertion. Compared to manual needle placement, robots offer the potential to make the procedures more precise and safer.

In this project, you will develop an image guided robotic needle placement system using the Robot Operating System (ROS) framework. You will use a depth camera (Kinect Azure by Microsoft) mounted on a robot arm (Panda by Franka Emika) to record 3D images of a chest phantom. You will need to find the transformation between the robot's endeffector and the camera with an eye-in-hand calibration. Using this transformation you will be able to stitch the individual images to a combined scan while the robot drives the camera around the phantom. You will then register this scan to a high resolution model, obtained from computer tomography. Within the high resolution model a target for the needle will be given. You will need to perform trajectory planning to find a collision free and kinematically feasible path to the target. Lastly, you will exchange the camera for a needle (mock-up) and let the robot perform the insertion.

Project Groups: The project work will be conducted in groups of six to eight students. To be eligible you need to submit the registration form via e-mail to robin.mieling@tuhh.de by the 11th of April.

Lab Access: You will start developing your solution with the help of a simulator. Towards the second half of the semester each group will be assigned one weekly time slot to work in the robot lab. The lab will be available to you during your lab times on your lab day. Access to the lab will require safety instructions that you have to participate in before working in our lab. Therefore, all group members must be present and on time for their first lab session.

Requirements: The following requirements are **mandatory** and need to be fulfilled in order to successfully complete this project:

- Attend to the first lecture on **4th of April**. If you cannot make it, write an email to robin.mieling@tuhh.de beforehand.
- Submit the registration form for the project by the **11th of April**.
- Submit a project plan including a sketch of the necessary interfaces between the components of your ROS application, tasks assigned to each group member, assigned project leaders and a weekly time plan by the **25th of April**.
- Submit **weekly reports** via StudIP in your group folder starting in May. Briefly state the contribution of each team member, the progress achieved in each part of the project as well as any problems you may have encountered. Team members not mentioned in **more than two** of the weekly reports will be considered inactive and excluded from the project.
- Submit a working inverse kinematics by the **16th of May**.
- Present your needle insertion system in your last lab session (**TBD 8th - 12th of July**).
- Describe your results and choices in a scientific paper consisting of approximately 5 pages due by the **1st of September**. State and explain every assumption made. Provide sources for all formulas you use.

Further deatils on the time table and additional subgoals can be found in the provided timetable.

Consultation Hours: You may consult the teaching assistants via email or in person during lab times or by appointment.

Recommendations: Remember to test scripts concerning the robot in the simulation environment available via Stud.IP before running them in the lab.

Consider the following work packages as suggestions on how to split the work within your group. You can always find alternative solutions as long as you keep the above requirements. All solutions should be implemented as ROS nodes, so that they can be easily integrated in the final application.

We recommend that Work Package 1 is solved by all group members together. The rest of the work can be divided, a possible division is between the robot movement team and the vision team.

Work package 1: Robot kinematics
In the final application you will need to move the robot to perform calibration, registration and the needle insertion. The robot works in the joint space, however, you will also need to move in Cartesian space at least for the linear motion during needle insertion. Therefore, it is important to convert the joint positions to a robot pose in Cartesian space and vice versa. Solve and implement the solutions to the Direct and Inverse Kinematics. For testing and verification of your implementation use the simulator. You can get the current joint positions from the `/joint_states` topic. You can get the current cartesian position of the end effecor using the transforms published by the `robot_state_publisher` on the topic `/tf`. From the console, you can look it up with `rosrun tf tf_echo panda_link0 panda_link8`. Also read up on ROS tf.

Work package 2: Trajectory planning
In order to move the robot to a desired target you need to send the robot a continuous trajectory of joint positions (at 1000 Hz). You should plan the full trajectory first, before starting to send the robot commands. You can find an example on how to send continuous joint commands to the robot in the file
`~/catkin_ws/src/franka_ros/franka_example_controllers/src/test_move.cpp`. You can test the trajectory planning in the simulator.

Work package 3: Robotic Scanning
The acquisition of camera images at different poses requires a scanning node that syncronizes image acquisition with robotic motion. Once the trajectory planning is functional, you will need to move the robot to different poses and automatically acquire image data for subsequent calibration/model registration.

Work package 4: Needle Calibration and Insertion Path
For the precise placement of the needle, you need to extend the kinematic chain to include the needle by identifying orientation and needle tip position. Additionally, needle insertion requires the movement in cartesian space, so you need to combine your inverse kinematics and trajectory planning nodes to generate cartesian trajectories. The poses for the desired insertion need to be calculated based on the given entry and target position obtained after model registration. Lastly, the needle need to keep a safe distance to bones for the actual needle placement the trajectories of the robot.

Work package 5: Camera calibration
The Kinect Azure has an RGB and a depth camera. You need to calibrate the Kinect so that it captures the true geometries of the world. This involves the intrinsic calibrations of both the RGB and the depth camera, as well as finding the transformation between the RGB and the depth camera frame, called extrinsic calibration. We will provide you a set of images capturing a checkerboard calibration object, from which you can calculate the calibration. We will also provide a reference calibration for comparison.

Work package 6: Eye-in-hand calibration
In order to stitch the pointclouds of the chest phantom, you need to know the transformation between the mounted camera ("eye") and the robot's end effector ("hand"). For this purpose you will need to move the robot to different poses and estimate the pose of the checkerboard in the images. Then, you will need to implement an algorithm to solve the hand-eye calibration with the set of robot and checkerboard poses as an input. We will provide you a set of robot poses, corresponding images of the camera capturing a checkerboard object, and the true eye-in-hand transformation as a reference and to test your implementation without needing the real robot. After validating your approach with the given data, you need to implement and test the calibration in your own system. Use the robotic scanning node for data acquisition if ready or initially start with manual acquisition.

Work package 7: Model registration and stitching
In order to obtain a 3D Scan of the chest phantom you will need to drive the camera around the phantom. Based on the known robot poses and the transformation from end effector to camera you can then register the individual pointclouds and stitch the data to one combined scan. Afterwards, you can register it to a high resolution model of the phantom which you will obtain from us in the form of a CAD file. For the start of the development we will provide you a set of 3D pointclouds and the robot poses at which these pointclouds were captured, so you will be able to test pointcloud registration. Subsequently, you will be able to perform the registration to the CAD model. Lastly, you will need to implement the selection of a target for the needle insertion.

Bonus Points: You may receive up to 10 bonus points that will be added to the points you obtain in the written examination for

- active participation during lab sessions,
- regularity of weekly reports,
- quality of your final presentation and the subsequent discussion,
- quality of submitted software (reasonable structure, sufficient commenting, performance during final presentation),
- plausibility of chosen algorithms and quality of their implementation/incorporation into your work,
- your ability to critically evaluate results,
- creativity and implementation of additional features,
- content and completeness of the final report including list detailing contributions of each author,
- and quality of writing (structure, appropriate use of figures and tables, no grammar or spelling errors).