Individual Lab Report 2 - Progress Review 1

Autonomous Reaming for Total Hip Replacement

HIPSTER | ARTHuR

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Team C:

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1 Individual Progress

Since the last ILR (for the Sensors and Motors Lab), I was responsible for designing the high-level architecture of the Controls Subsystem and identifying tools that would enable us to implement this architecture.

After extensive research over the past two weeks, we decided to pursue Model-Predictive Control (MPC) to control our manipulator for our autonomous reaming task. The reasons for choosing MPC over other control methods are that while MPC is more challenging to implement, other controllers would not be as robust, nor as optimal (unless extensively tuned, which could take weeks and a lot of testing). Furthermore, implementing constraints on other control methods would not be as easy or robust since the controller itself may not be aware these constraints, which could lead to unexpected behavior in the plant. For example, there will be joint torque constraints on the system. Other control methods would not easily be aware of these limits and output unreasonable torques. While the low-level controller within our manipulator would throttle these torques, resulting in unexpected behavior. MPC, on the other hand, would be aware of these constraints and would compensate the input into the plant based on these constraints, resulting in expected behavior.

Below is a high-level controls block diagram that will dictate the architecture of our system (Figure 1). The main constraints that the MPC will take into account are the linearized dynamics (Figure 3), the maximum force on the end-effector, the maximum velocity of the end-effector, the x- and y- axis positional error tolerances. Joint torque and force limit constraints will be added as we progress further into implementation. The objective of the MPC is to minimize the distance along the z-axis from the current z-position to the desired z-position, as well as minimize the force applied onto the acetabulum. MPC will then provide the optimal force to apply to the system, which will then be given to the UR5 under Force Control. Figure 2 shows the coordinate frame of the x-,y-, and z-axes discussed here. The MPC will then receive feedback through external force/torque readings from a force/torque sensor on the wrist, and the 6D pose of the end-effector. It will use this feedback to calculate the optimal force for the next time step.

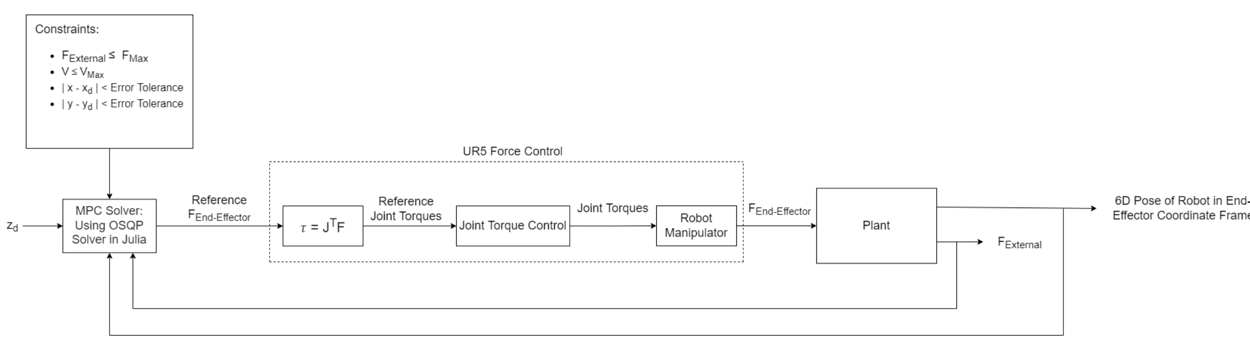

Figure 1: High-Level Control Block Diagram

Figure 2: Coordinate Frame of the End-Effector Reamer

$$\min_{u_k, k\epsilon[1,H]} \quad \frac{1}{2}(z_H - zd)^T Q (z_H - zd) + \sum_{k=1}^{H-1} \frac{1}{2}(z_k - zd)^T Q (z_k - zd) + \frac{1}{2} u_k^T R u_k$$

$$\text{s.t.} \quad \begin{bmatrix} x_{k+1} \\ \dot{x}_{k+1} \\ y_{k+1} \\ \dot{y}_{k+1} \\ z_{k+1} \\ \dot{z}_{k+1} \\ \phi_{k+1} \\ \dot{\phi}_{k+1} \\ \theta_{k+1} \\ \dot{\theta}_{k+1} \\ \psi_{k+1} \\ \dot{\psi}_{k+1} \end{bmatrix} = \begin{bmatrix} x_k + \dot{x}_k h \\ \dot{x}_k + u_{x,k} h + F_{x,k} h \\ y_k + \dot{y}_k h \\ \dot{y}_k + u_{y,k} h + F_{y,k} h \\ z_k + \dot{z}_k h \\ \dot{z}_k + u_{z,k} h + F_{z,k} h \\ \phi_k + \dot{\phi}_k h \\ \dot{\phi}_k + u_{\phi,k} h + M_{\phi,k} h \\ \theta_k + \dot{\theta}_k h \\ \dot{\theta}_k + u_{\theta,k} h + M_{\theta,k} h \\ \psi_k + \dot{\psi}_k h \\ \dot{\psi}_k + u_{\psi,k} h + M_{\psi,k} h \end{bmatrix}$$

$$||F_{external}|| \leq F_{Max}$$

$$||V_k|| \leq V_{Max}$$

$$||x_k - x_d|| \leq \varepsilon$$

$$||y_k - y_d|| \leq \varepsilon$$

Figure 3: The Optimal Control Problem in the MPC to Minimize

The Optimal Control Problem for the MPC will be implemented using Operator Splitting Quadratic Program (OSQP) implemented using the Julia coding language.

In addition to my responsibilities core responsibilities, I also collaborated with Parker on the PCB Power Distribution Board Assignment sanity checking and fixing small errors that might've led to the PCB failure. I also brainstormed with Parker on some ideas for mechanically attaching the reamer to the manipulator wrist.

2 Challenges

The main challenges during this progress review was developing and writing the optimal control problem from scratch and figuring out how this MPC would fit into the larger control system (i.e. what is effort, u, that is being fed into the lower-level manipulator controller). This was a challenge because of my lack of experience developing the dynamic models for the optimal control problem, especially force-based MPCs. These challenges were addressed through a mix of research, iterative brainstorming and development, and asking for advice from professors such as Professor Zachary Manchester, who is the professor for the Optimal Controls and Reinforcement Learning course at CMU.

3 Team Work

A summary of each team member's contributions towards the MRSD project and Project Course can be found in the Table below (Table 1).

Table 1: Team Member Contributions and Collaborations Towards the MRSD Project and Project Course

Team Member	Contributions for MRSD Project & Project Course

Anthony Kyu	• Led and collaborated with Sundaram on the design of the high-level controls architecture
	  ○ Designing the controls block diagram
	  ○ Defining constraints for our controls system
	  ○ Creating the linear dynamics for our model predictive control
	  ○ Did extensive research to determine how similar MPCs are implemented
	• Collaborated with Parker on the PCB Assignment, sanity checking the circuit diagram and pointing out key issues that could lead to shorting
	• Brainstormed a few mechanical design ideas with Parker to mount the reamer to the end-effector

Parker Hill	• Coordinated and obtained the reamer handle from our company sponsor, Smith & Nephew • Elicited motor requirements for the reaming assembly • Created rough CAD models for the reamer handle and the end-effector adapter, and brainstormed ideas with Anthony • Led and collaborated with Anthony on doing the Power Distribution Board PCB Assignment for the Project Course
Sundaram Seivur	• Collaborated with Anthony in conceptualizing the optimal control problem for the controls system • Did a significant amount of literature review to help determine and decide between Model-Predictive Control and hybrid force position control • Facilitated discussions with Professor Kroemer and Smith & Nephew to obtain new arm for the team to use

Kaushik Balasundar	• Worked on the registration problem
	  ○ Researched various types of registration algorithms
	  ○ Integrated Open3D with ROS
	  ○ Wrote a script for converting a mesh file to a point cloud
	  ○ Implemented a preliminary ICP registration algorithm with Open3D for local and global registration
	  ○ Tested ICP with some toy examples to verify functionality

Gunjan Sethi	• Worked on further developing ROS package for the Atracsys camera, adding pose detection • Currently facing challenges with code reliability during marker detection • Tested camera discovery and geometry file loading functionality for robustness • Prepared for Progress Review 1 and presentation

4 Plans

Before the next progress review, I plan to refine and implement the Optimal Control Problem in the Julia Programming Language, using OSQP to solve the Optimal Control Problem. Then, I plan on integrating this code with the larger control loop, as indicated by the Control Block Diagram, and integrate this into simulation and test the MPC controller on the UR5 for Progress Review 2.

Besides my main goals for the MRSD project, I also plan on collaborating with Parker to improve initial mechanical designs and complete assignments given by the Project Course.