

Multi-Layer Robotics Teleoperation for Franka Emika Panda

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Introduction

The Franka Emika Panda arm is a 7-joint collaborative robot that was developed in Munich, Germany by Franka Emika, which is used for precision tasks, research and automation fields. The Franka has integrated torque sensors in all 7 of its joints which enables it to have very high levels of sensitivity in regard to when it has feedback from forces that interacts with it, helping it do collision detection and safe human-robot collaboration.

The Franka can be used to interact with advanced control and programming software and has applications such as being integrated with research scaffolds such as ROS, MuJoCo and Unity that has uses such as simulation and teleoperation. Furthermore, the Franka is used widely in both academia and industry research to perform various manipulation tasks, machine learning and creating immersive virtual reality control outputs.

Elaborating on the concept mentioned before, imitation learning is a machine learning technique that is exploring when a robot learns to perform a task by observing and recreating demonstrations it has been taught, such as human teleoperations and pre-recorded tasks. This is highly effective for complex manipulation tasks where manually programming a control policy is complex or inefficient. This would allow the robot to learn behaviours from human demonstrations via interfaces such as Virtual Reality tools or motion tracking. We use this often, in combination with simulation tools such as ROS and Unity pipelines, to safely train, test and iterate on learned techniques before deploying them to physical software.

Despite the extensive development regarding the research into imitation learning, the current methods face a few key limitations such as high communication latency and synchronization issues when it comes to the real time aspects of the real-time virtual reality teleoperation frameworks, and then the difficulty of trying to integrate system

designs with machine learning frameworks. In addition to this, training policies in simulation doesn't always guarantee to translate properly when it came to the actual robot; which creates a structural reality gap.

My project aim was to investigate how integrating robotic-based simulation environments (MuJoCo for my project) with the Robot Operating System (ROS) pipelines and virtual reality (Meta Quest/Unity) visualisation for robotic manipulation control using the Franka arm. This idea would be carried out via the establishment of a multi-layer connection bridge which would connect our hardware/simulation control points via a ROS-TCP-Connector link to map joint states, transformations and positional data into an immersive VR interface, in real time.

There is also the objective to develop executive scripts to handle the kinematics of the Franka for its various joints, handle the transformations of the coordinates and the data publishing loops between the various physics engines, the middle communication layer and the display at the end.

A desired output for this would be a functional, interactive virtual reality simulation workspace that will enable real-time teleoperation regarding the Franka arm and its control loops, which provides the foundations for safe imitation learning policy training.

Methodology

The research involved in this project supports a quantitative, experimental systems engineering approach which focuses on designing, implementing and establishing a real-time virtual reality teleoperation and simulation framework. The primary focus is to ensure a multi-layer connection bridge that links physical control interfaces and robotic physics engines to set the foundations for imitation learning policy training.

The experimental setup used for this project combines the three different, primary computational environments to handle the kinematics, data publishing loops and the immersive visualization required for imitation learning. These are:

- **The Simulation:** MuJoCo serves as the core engine for the physics aspects such as modelling the 7 DOF Franka Emika arm, the computation of the dynamics of the joints and detecting collisions around the Franka. The arm is a very expensive piece of technology so this collision detection is vital so there is no damage to it.
- **The Middleware:** The Robot Operating System (ROS) manages node-based data distribution, message passing and our communication loops.
- **The Visualization and Teleoperation:** This regards Unity, controlled by a Meta Quest Virtual Reality headset, which would then provide an interactive virtual reality workspace that would link between the human hand and controller movements.

To bridge the gap between the Virtual Reality headset and the simulated physics, the system relies on a two-way communication pipeline. This is done by using a custom ROS-TCP-Connector link; which then makes sure positional data and hand movements from the VR headset are translated in real time into joint states and transformation matrices for the simulation loop.

This is done in the background where custom scripts manage the core mechanics of the system:

- Translating coordinates so that movements in the virtual workspace match the simulation space.
- Running the data publishing loops that keep MuJoCo, the communication aspect mentioned prior, and the Virtual Reality display in constant synchronization.
- The calculations regarding the mathematical kinematics and using the Jacobian matrix to map end-effector velocities to joint-space velocities for the Franka arm.

To translate human hand movements from the virtual reality interface into coordinated movement for the Franka, the system relies on velocity mapping via a Jacobian matrix. It has been found that in robotic manipulation, the Jacobian serves as the mathematical-based link between the Cartesian space (the actual physical space around where the human hand moves the Virtual Reality controller) and joint space (the individual rotational angles of each of the joints on the Franka). Because the Virtual Reality controller provides linear and rotational velocities for the user's hand, the Jacobian matrix determines precisely how each of the Franka's seven joints needs to rotate to achieve the exact end-effector movement in real time. This makes sure that the virtual robot arm mirrors the human inputs smoothly and accurately within the simulation build on MuJoCo.

The system is designed to track high-frequency kinematic and performance metrics throughout the execution loops. This is achieved by:

- **Joint States and Transformations:** Real-time position logging of the Franka arm's 7 joints, their velocities and the end-effector coordinates across the ROS-TCP bridge.
- **Tracking Telemetry:** Positional and oriental data collected from the Meta Quest controllers and headset from the position of the Unity Coordinate system.

System performance and kinematic inconsistency are scaled using quantitative measures:

- **Latency Profiling:** Determining how long it takes for motion via the Meta Quest headset to be detected through the ROS-TCP-Connector and update inside the MuJoCo physics loop, ensuring the system stays active.

- **Kinematic Accuracy:** Checking target positions created through the Virtual Reality interface against the Franka model's both forward and inverse kinematics to make sure nothing drifts and lines up spatially.

Safety protocols must be strictly maintained throughout this research process for various reasons. Collaboration between humans and robots, specifically regarding the Franka, is prioritised by utilising the Franka Emika's internal torque sensors and automated collision detection mechanisms. Any work done in this project must follow institutional health and safety regulations.

This was demonstrated even further by a strict lab rule that throughout the experimental process, any physical interaction with the Franka was prohibited until successful outputs in the simulations created have been achieved. This prerequisite is essential because unsuccessful scripts or control policies can cause unpredictable, unsafe movements that may risk damaging a very expensive, vital piece of precision hardware or creating an unsafe environment for the people working in the robotics lab. By making sure that all simulations are tested thoroughly via MuJoCo software and environments created in Unity as a first step, any potential risks can be caught in advance.

Results

While this project was able to successfully establish the complete simulation architecture (which would include the Unity VR interface, the ROS-TCP-Connector bridge, MuJoCo simulation modelling, and custom scripting regarding the kinematics using the Jacobian matrix mentioned prior), timing issues and the learning curve of trying to self-teach and become comfortable using Linux, ROS, and MuJoCo from scratch meant that actually working on the physical Franka arm hardware had to be put aside. Furthermore, the scope focused entirely on building and determining the virtual framework required for the robot, meaning the full project objective was not completed within the desired time frame. Additionally, if this project was to be carried on further, the framework currently created only exists within a simulation and Virtual Reality environment, scripts tested here will most likely find a reality gap when transferred to physical hardware due to real life issues such as sensor noise.

Future Work

Furthering on some of the issues faced within this research project, there is a few suggestions for further work that could be taken to ensure the original project aims were completed, and that practical implementations of the simulations could be successful. These suggestions are designed to bridge the remaining gaps that were not covered within the research period; connecting better the current simulation framework and full physical deployment, since they are the primary scaffold of this project.

- **Imitation learning implementation:** This would reflect further use of the virtual teleoperation workspace to source human demonstration datasets for training and testing control policies safely.
- **Lab-approved documentation:** This would be the creation of technical guides detailing Linux, ROS, Apptainer and Unity to streamline onboarding processes just to make it easier for future scholars working on similar projects.
- **Hardware Validation:** This would be the deployment of the simulation pipeline onto the physical Franka Emika Panda arm to test how the control loop scripts created and the Jacobian mappings handle real-world friction and sensor noise.

Reflections

While I realise my journey during this research period has been nowhere near linear, I have grown significantly and I am very proud of myself for that. I feel much more comfortable communicating in a professional environment, I have developed robust coding skills that I want to pursue post-placement and I have built up core research skills such as: learning how to translate my raw data from my experimentations into a written report. This has all ultimately rebuilt my self confidence in the field.

Going into this project in June, I felt very nervous and carried an on-going fear that I would be out of my depth due to having no previous lab experience at that level. This left me anxious about whether I could handle a complex robotics and Virtual Reality project such as the one I was presented. Those initial concerns felt prevalent, especially when getting my keycard and stepping into the lab for the first time. I felt I didn't belong in such a highly valued research environment because I didn't have the experience. However, as the project progressed started to feel more comfortable and confident in that I am capable of being in such a high-level, academic environment.

The road to get this far into my project wasn't without very distinct and technical obstacles. Early on into the summer, I faced the issue that the Virtual Reality headset provided to me by my project supervisor was incompatible with the operating system of which I was using, Linux, and so therefore I had to completely pivot my plans in order to trouble shoot it which in turn, caused time delays. I also struggled frequently with remembering specific Apptainer names on Linux which would essentially lock me out of my work causing me to have to start from scratch and iron out those issues with my workflow until I was able to acknowledge where I would go wrong. I realised that if I was to progress further in my research, it was best practice to record everything just for convenience and ease. Finally, balancing time management to make sure everything was completed at a reasonable pace was also another steep learning curve which proved to me to be a steep juggling act and something I would work on more if I was to further this project.

The reality of this project also looked very different from what I had originally expected. I had originally envisioned working in a collaborative group setting, but instead I found I was doing most of this project independently. This meant I had to rethink my strategy of how I approached this project as I had never undergone a task of this severity independently before. In addition, I didn't reach the desired output I had originally hoped for by the end of my summer research period due to prior mentioned time constraints. Yet when it comes to reflections, I have learned an enormous amount during my summer; developing my technical abilities within the lab, acquiring newfound research skills and resistance within myself that matters to me far more than achieving a goal set at the beginning of the research period. If I was going to repeat this style of project in the future, I would focus on time management and ensuring I am properly prepared so my timescales remain on track so I can achieve the output I want whilst also doing research into all the new software I would be using, such as ROS and Linux in my Franka research project) before the scheme so that I would be at a head start.

Taking full ownership of this project forced me to have a unique twist on the term leadership and how I managed myself. I essentially had to independently lead the entire scope of my research, meaning teaching myself brand-new software environments like ROS, MuJoCo and Unity from scratch with limited guidance. This meant taking the initiative to organise meetings with my project supervisor, proactively diagnosing roadblocks such as the Meta-Quest headset-Linux incompatibility and coming up with my own solutions which I presented to my supervisor. Linking this with the key Laidlaw value of Leadership, this project became a lesson in authentic self-management, resilience under pressure and self-accountability. I felt I experienced the Laidlaw value of ambition throughout my project. I had ambition to achieve the greatest amount I could during this research period, taking every opportunity I was given and exploring how I could learn from it. I believe ambition is the key driver for a career within research as lacking drive keeps you stagnant, which would massively limit how much research can progress.

Also, operating without a direct safety net has essentially changed my relationship with how I pursue technical failure. In traditional environments such as failure within school where there are structured problem sets within definite answers, but this summer taught me how sometimes the answer is not as clear. When the communication framework broke down with the ROS-TCP-Connector or when the simulation scripts I had built didn't work as in a way which I desired, there was no answer sheet or mark scheme which could help me out. I had to learn how to systematically deconstruct and solve these issues from a set of first principles, figure out from what piece of software I was using caused which issue or which line of code produced an error. This transition from a passive learner waiting for instructions to an active, self-guided researcher is most definitely the most important change I have underwent throughout my Laidlaw research project; shifting my future academic identity as someone who just copies the

traditional route into someone who is curious and is driven by initiative to investigate why things happen.

I aspire to share this project with others, as I think networking is vital for further advancements, and I plan to attend the Laidlaw Research Conference in London this coming October, offering me the opportunity of a platform for professional networking and developing public speaking skills. Looking further into my future, this independent summer of research has profoundly shaped my academic and career trajectory. This project has re-sparked my curiosity that I had as a child towards engineering, and I was inspired to be surrounded by like-minded people who share my ambitions. Battling with complex systems engineering entirely on my own has solidified my long-term goals and helped me realise that I would rather have a path in research over a career in industry, as I feel the former would be a better fit for me. I realize I thrive in environment where I'm given the autonomy to pursue open-ended problems independently and contribute to technologies that push boundaries rather than just stick to what is already known. I strive to develop new technology and change lives for the better through a career in research.

I want to pursue a master's degree specializing in medical robotics in Germany with then pursuing a long-term research career within the country's advanced medical engineering sector. I have the goal of robotics within Germany as there is a huge intersection between high-precision control, real-time feedback and vast development within the field I love. Surgical robotics and AI-based medical software demand zero tolerance for error, which in a way mirrors the collision detection requirements I had to develop with my time working on the Franka, so I believe this research project has been such an amazing opportunity for future development. I want to be able to connect with like-minded scholars to further progress the ideas worked on in my research project such as the topic of imitation learning.

This particular academic path will allow me to build directly upon certain techniques learnt from my current research period such as the control frameworks and kinematic principles explored during the scholarship. To support this transition, I have been actively building a financial buffer over the past year to self-fund a blocked account whilst also targeting competitive funding such as the DAAD scholarship. This has been made possible due to the independence, technical skills and leadership developed throughout this Laidlaw scholarship this summer and I so appreciate of how it has taught me how to communicate professionally which will help in graduate applications.

Ultimately, this project has not just deepened my technical skills within robotics simulations and teleoperations but has given me resilience and the academic backing necessary to turn these long-term international research goals into reality. It has given me the ability to realise I can connect with others and develop my skills as a young, research scholar.

