Implementation of advanced teleoperation with haptic feedback

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Popular science summary of master thesis
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One of the difficulties with implementing automation using robots is programming tasks that include interaction with an object, such as lifting a box. The most natural way of transferring these skills is by demonstration, to show the robot how to do a motion instead of programming its joints to move a certain angle at a certain time. By using haptic feedback the demonstration can be made to feel more natural for the programmer by giving them a feel for the forces that are affecting the robot. This way of programming robots will greatly improve the speed and ease of which tasks, where a robot interacts with an object can be programmed, moving the use of robotics even closer to everyday tasks.

This master thesis achieves this by implementing teleoperation between a real and virtual robot, the virtual robot mimics the real robot's motion. The implemented teleoperation includes haptic feedback, where the implementation of a force/torque (F/T) sensor and a teaching handle to enhance the user experience further. The setup can be seen in Figure 1. As the integrated F/T sensor included in the real robot did not prove up to the task another F/T sensor was implemented and externally mounted on the tip of the robot arm. This tip of the robot arm is called its end effector.

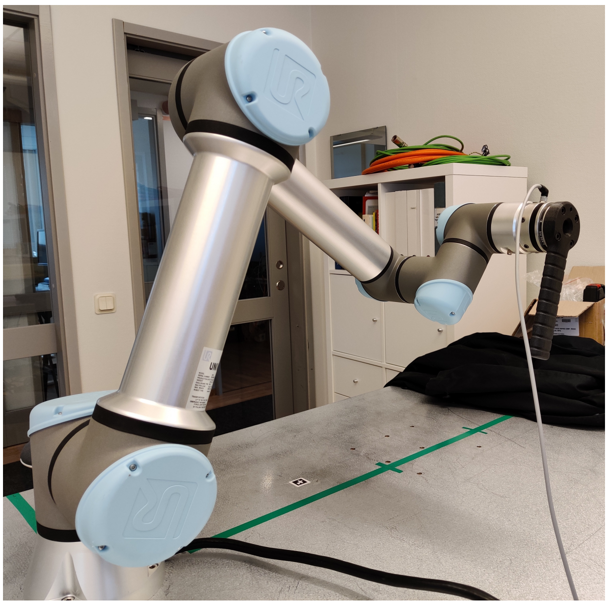

Figure 1: The setup for the algorithm. The robot is an UR5e, the F/T sensor is fixed on the end effector, the handle is fixed to the F/T sensor. The robot and F/T sensor is connected to a laptop were the virtual robot and the algorithm run.

The implemented algorithm was tested with four main questions.

- Does the algorithm maintain the position and orientation offsets between the two robots' end effectors during motions in space without any obstructions (i.e, free-space)?
- Does the haptic feedback consistently and intuitively reflect interaction with an object?
- Are the physical limitations of the robots enforced?
- What is the impact of the included F/T sensor?

The results of these tests are a reliable haptic interface. The implemented algorithm maintains the position and orientation offsets between the two end effectors of the robots as can be seen in Figure 2. It also intuitively and consistently reflect the interaction with an object as seen in Figure 3. The physical limitations are also enforced. However, the test to evaluate the impact of the included F/T sensor was inconclusive.

The test to determine the impact of the included F/T sensor was done by providing the same motion to the real robot both when the F/T sensor was not included and when it was. This test had the flaw that the errors in the reproduction of the movements were large enough to result in no clear impact of the F/T sensor on the performance of the algorithm. The improvement in performance that was expected from the inclusion of the F/T sensor, in theory, did not appear in the result. Other ways of investigating the impact of the included F/T sensor were theorised but not implemented due to time constraints.

The largest identified source of errors in the implemented algorithm was the low update rate of some of its threads. This low frequency expressed itself as a delay between the real and virtual robots. This delay in turn resulted in a less intuitive haptic response during movements of the real robot in a direction that was not the same as the one that the virtual robot was moving in.

This problem resulted in a trade off between the error in position and orientation between the two end effectors and how intuitive the haptic response was experienced. If the error in position and orientation was reduced by making the controller more aggressive, the intuitive haptic response suffered when the two end effectors due to the delay were moving in different directions.

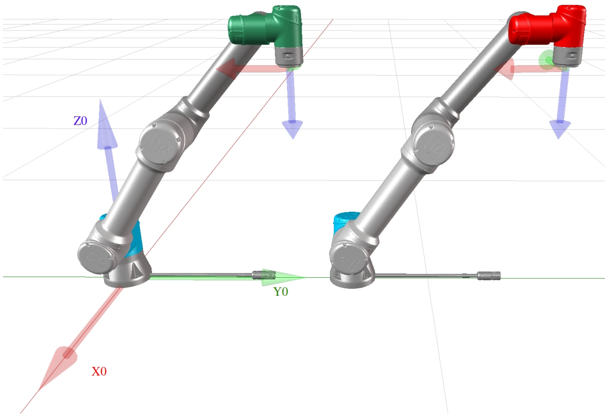

Figure 2: Position and orientation offset test. The real robot is marked with a green coloured head while the virtual robot is marked with a red coloured head. The base frame is marked as 0 frame. The frames of the end effectors have been included for both robots to visualize their orientation.

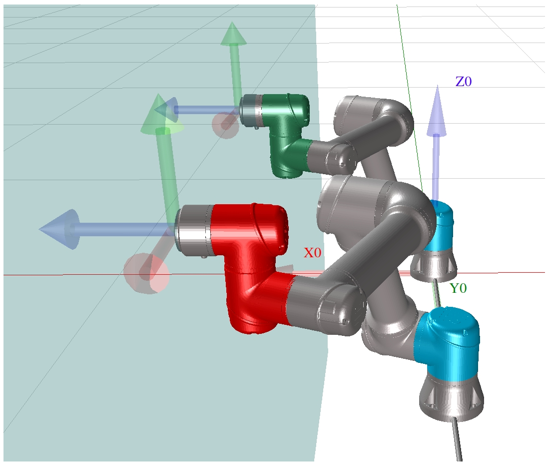

Figure 3: Interaction with an object test. The real robot is marked with a green coloured head while the virtual robot is marked with a red coloured head. The object is the virtual wall included in cyan. The base frame is marked as 0 frame. The frames of the end effectors have been included for both robots to visualize their orientation.

The impacts of this interplay were lessened by reducing the mass of the virtual robot to 25% of the real robot's and improving the frequency of the regulator thread. Although improvements were made within the limits of the time constraints the impacts of this error source were still felt on faster movements. However, as these movements were fast enough to violate some of the assumptions made in the theory of the algorithm was the remaining impact deemed acceptable.

One of the included improvements was the addition of the F/T sensor. The integrated F/T sensor in the UR5e robot was first investigated as a source for the forces and torques used by the algorithm. However, the included compensation for the integrated F/T sensor did have problems with shifting orientations resulting in an inconsistent and sometimes wrong frame of reference for the forces and torques. As the internal F/T sensor is not capable to perform its task an external F/T sensor was used.

One of the most important performance demands on this implementation is what is called Singularity-free operation. One of the most important matrices in the algorithm is the Jacobian matrix that is used to transfer the joint velocity of the robot's joints into the movement of the end effector. This matrix is dependent on the joint angles of the robot's joints, as there are two robots will there be two Jacobians. This dependence on the configuration of the robot results in the Jacobian becoming a singular matrix during certain configurations called singularities. During these singularities one can not take the matrix inverse of the Jacobian.

This becomes a problem for a part of the algorithm Γ which contains the Jacobians and are inverted during the calculation of the control signal. In order to avoid this problem was a damped pseudo-inverse of Γ used to calculate the inverse of the control signal.

In Figure 2 both robots can be seen in singularities and there configurations were included in the test during free-space motion, proving its singularity-free operation.

In conclusion, the implemented algorithm resulted in a reliable and adequate intuitive haptic interface with room for improvement regarding the update frequency of its threads. The theoretical improvement in performance that was expected from the inclusion of the F/T sensor was not observed due to limitations in the testing. No other tests were implemented due to time constraints on the project.