ROBOTICS
AND
MECHATRONICS

Design and realisation of a haptic interface between a ReFlex TakkTile and an Omega 7 Haptic Device

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BSc Report

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Summary

This thesis is part of the i-Botics project. It is founded as an independent research center by TNO and University of Twente. The research is mainly concerned with interaction robotics, namely telerobotics and exoskeletons.

Telerobotics deals with remote controlled robots. These robots are send to remote location without the operator of the robot being present. Telepresence and teleoperations are used to allow the operator to control the robot with remote presence. To achieve this remote presence for the operator, several technological approaches can be used. Haptics is one of these.

This thesis is a design oriented project within the telerobotics research field of i-Botics. The goal of this thesis is to create an haptic interface between a robotic hand (ReFlex TakkTile) - mounted on a remotely controlled robot - and the control unit for the user (Omega 7 Haptic Device). This haptic interface is created to allow the user to do remote manipulation. This should allow for interaction with objects which are in the remote environment.

First, an analysis was done to investigate possible implementations for the haptic interface. Both side of the haptic interface were investigated based on their control possibilities. From that point onwards, a bond graph approach was used to identify four possible haptic interfaces. Based on the available hardware, an impedance type and direct type interface are suitable. These interfaces are the control layers between the ReFlex TakkTile and the Omega 7.

In the implementation phase, both haptic interfaces were constructed and tested. The interfaces were implemented using a Robot Operating System (ROS) as middleware. This allows for easy communication between the robotic hand and the control unit. During the construction of the impedance type interface it became clear that it was not a suitable interface, because the force control of the ReFlex TakkTile did not respond well. Therefore, the direct approach was chosen for the remainder of the project. This interface was successfully implemented.

Tests were executed to test the functionality of this interface. From this it was clear that the interface is best suited for stiff environments and that it functions optimal when the speed of the finger of the ReFlex Takktile is kept low. When the speed of interaction is high, the interface did not respond adequately due too time delays in the system. Furthermore, the interface was not tested wirelessly due to time constrains.

Samenvatting

Deze scriptie is onderdeel van het i-Botics project. Dit project is opgericht door TNO en Universiteit Twente als onafhankelijk onderzoekscentrum. De focus van het onderzoek is gericht op interactie robotica. In het specifiek: telerobotica en exoskeletons.

Telerobotica houdt zich bezig met op afstand bestuurbare robots. Deze robots worden naar afgelegen locaties gestuurd zonder dat de bestuurder daar daadwerkelijk aanwezig is. Telepresentie en teleoperaties kunnen worden gebruikt om de bestuurder van de robot meer het gevoel te geven dat hij of zij daadwerkelijk bij de robot aanwezig is of zelfs de robot kan 'zijn'. Meerdere technologieën kunnen worden gebruikt om deze graad van 'situationeel bewustzijn' te creëren. Haptics is één van de mogelijkheden.

Deze scriptie is ontwerp geörienteerd en is een onderdeel binnen het onderzoeksgebied van de telerobotica. Het doel van deze scriptie is om een haptische interface te maken tussen een robot hand (ReFlex Takktile) - die gemonteerd is op een op afstand bestuurbare robot - en een besturingseenheid (Omega 7 Haptic Device). Deze haptische interface is gemaakt om de bestuurder in staat te stellen de robot op afstand te besturen. Hierdoor kan de bestuurder interactie hebben met voorwerpen die de robot vast kan pakken.

Eerst is een analyse gedaan naar mogelijke implementaties van de haptische interface. Er is gekeken naar beide kanten van de interface om te kijken naar mogelijkheden voor de aansturing. Met behulp van bondgraaf technieken zijn vier interfaces geïdentificeerd. Twee van deze vier interfaces werden geacht positieve resultaten te geven gebaseerd op beschikbare hardware. Dit zijn de impedantie interface en de directe interface aanpak. Deze interfaces vormen een plek waarin regeltechniek toegepast kan worden tussen de ReFlex TakkTile en de Omega 7.

In de implementatie fase zijn deze twee interfaces gerealiseerd en getest. Een besturingssysteem voor robots (ROS) was gebruikt als middleware voor de implementatie. Dit besturingssysteem maakt het mogelijk om makkelijk te kunnen communiceren tussen de robot hand en de besturingseenheid. Tijdens de realisatie van de impedantie interface is gebleken dat deze interface niet geschikt is, omdat de force controller van de ReFlex TakkTile niet goed reageerde op de commando's. Gedurende de rest van het project is daarom gekozen voor de implementatie van de directe interface. Deze interface is succesvol geïmplementeerd.

Tests zijn uitgevoerd om de functionaliteit van deze interface te testen. Hieruit bleek dat de interface het beste werkt in stijve omgevingen en dat de haptische terugkoppeling het beste werkt als de snelheid van de vingers van de ReFlex TakkTile laag is. Als deze snelheid hoog is resulteert dat in een slechtere reactie van de interface. Het systeem is niet draadloos getest vanwege tijdsrestricties.

Contents

1 Introduction

This assignment is part of a large robotic project at the i-Botics lab. The aim of this project is to create a robot which can be operated from a remote location to achieve a manipulation task. The robot consist out two RMP omni 50 systems which make up the base of the robot. Furthermore, a robotic arm (KUKA LWR 4+) is mounted on the base. This arm has a gripper (ReFlex TakkTile) connected to it. The robot is controlled from a control unit (Leo Universal Cockpit) and it gives the user audio, video and haptic feedback. Part of this control unit is an Omega 7 Haptic device which allows the user to control the robotic arm and gripper. The goal of this bachelor assignment is to create the haptic feedback interface between the Omega 7 haptic device and the ReFlex TakkTile.

The robotic hand has multiple pressure sensors in every finger to register interaction with the environment. This data can be used to provide haptic feedback to the user through the Omega 7 Haptic Device. This means that if the fingers of the ReFlex TakkTile hit an object, the user feels this object by means of force feedback in the Omega 7 Haptic Device. The goal of this assignment is to achieve reliable and realistic haptic feedback of the gripping action of the robotic hand. Although the ReFlex TakkTile has 4 degrees of freedom, only 3, controlled as one, degrees of freedom are used during this assignment. To create this haptic feedback a robust program needs to be developed in order to control the robotic hand appropriately. Currently, the robot runs on a Robotic Operating System (ROS) and is programmed in C++. Since the robot is designed to be modular, the code should also be modular. This means that programming should be done 'component-based' and that all the software should be reusable and independent of ROS.

To create this haptic interface a bond graph approach is used. This is a port-based modeling approach which is energy based and is a domain independent technique which allows interconnection between different domains (Mersha, 2014). The bond graph approach was used to identify four possible haptic interfaces. These interfaces are the control layers between the ReFlex TakkTile and the Omega 7. From the bond graphs, the corresponding control structures are derived. Based on early tests and analysis on the available hardware, a control structure was chosen to be implemented. The software is developed in ROS. The final demo allows the user to feel the gripping force of the ReFlex TakkTile while the the robot is situated at a remote location.

This bachelor thesis will give an overview of the haptic interface. First, some basic background information on haptic interfaces is given in chapter 2. From the background and project description, the requirements are identified in chapter 3. Then an analysis is done on haptic interfaces in chapter 4. Next, the design and implementation are presented in chapter 5, followed by the results and a discussion in chapter 6 and 7 respectively. Finally, a conclusion and recommendations are given in chapter 8 and 9 respectively.

2 Background

This section consists out of two parts. First, different types of haptic feedback will be addressed. This will give insight in how the user can experience these different types of haptic feedback. Then an overview is given of the setup that is used during this thesis project. Especially, the ReFlex TakkTile and the Omega 7 haptic device will be discussed there.

2.1 Haptic feedback

There are different approaches possible when it comes to providing haptic feedback to the user. Which type of haptic feedback is suitable, depends on the application. This section elaborates on different types of haptic feedback that are used most often.

2.1.1 Cutaneous feedback

This type of feedback can be perceived through the skin. There are lots of receptors in the skin which allow for this perception. Cutaneous feedback can be further subdivided into the following types of feedback which all can be perceived through the skin.

Tactile feedback
Tactile feedback allows humans to perceive pressure patterns on the skin. Therefore, humans are able to identify the shape and texture of objects. For this reason, tactile feedback is considered to be a very important type of haptic feedback for humans (Rubin, J., 2016).

Vibrotactile feedback
This is also called vibration feedback. This is a logical name since vibrotactile is all about vibrations. Humans are capable of detecting vibrations on the skin up to 1000 Hz. This means that the human skin is able to 'feel' sounds under the right conditions (Rubin, 2016a). Usually, this feedback is implemented by the use of vibrating actuators. Changes in pulse width and pulse rate can be used to modulate the intensity of the vibration (Chatterjee, 2008).

Thermal feedback
This last type of cutaneous feedback is based on the flow of heat energy. The human skin is very good in picking up temperature changes. By providing hot/cold sensations through conducting materials, thermal feedback can be simulated (Rubin, 2016b).

2.1.2 Force feedback

This type of feedback is perceived through muscles. There are lots of sensory organs present in the human muscles which can react to forces acting on the musculoskeletal system. With these sensory organs, humans are able to perceive force feedback.

In contrast to cutaneous feedback, force feedback applies forces to the user on larger parts of the body such as a finger or an arm. This is caused by the fact that the sensory organs in the muscles cannot pick up small changes in a muscle. For this reason, force feedback devices are usually much larger than cutaneous feedback devices.

Furthermore, there is a difference between resistive and active force feedback devices. Resistive haptic devices block certain movements the user wants to make. This restricts the motion of the user. Active force feedback does this as well, but it also can guide the user in the right direction by actively moving their body around. (Rubin, 2016c).

2.2 The robotic setup

The telerobotics project at the i-Botics lab at the University of Twente concerns a robot that consists of different hardware and software components. This section gives a quick overview of all these different parts. Figure 2.1 gives an overview of the total setup.

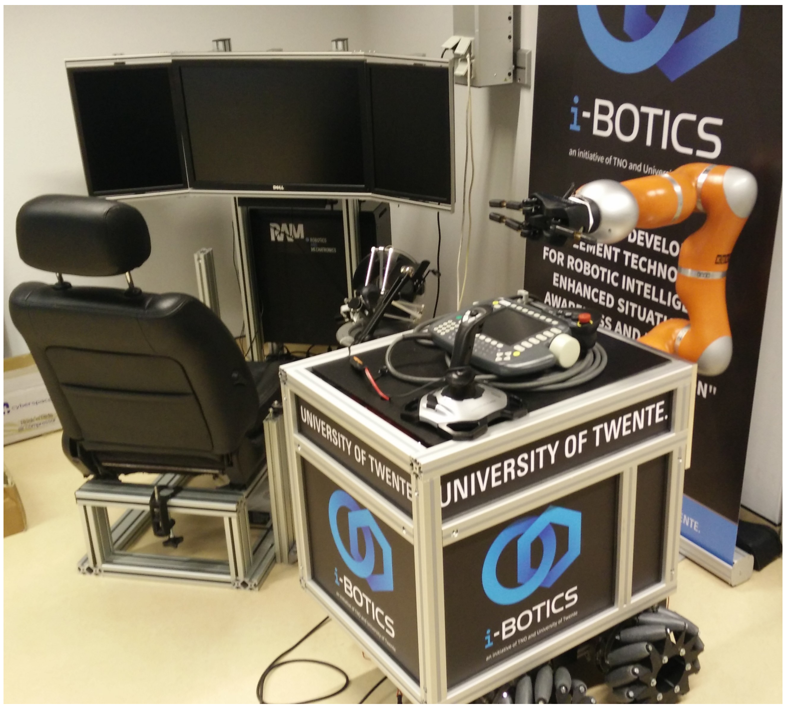


Figure 2.1: The robotic setup

2.2.1 Base

The base of the robot consist of a large box which holds the processors and batteries to power the robot. This box is placed on top of two RMP omni 50 segway systems which allows the robot to move omni-directionally. The two segway systems are rigidly connected to form a solid base. The wheels of the robot are chosen to be omni-directional wheels and can be driven independently from each other.

2.2.2 KUKA LWR 4+

On the side of the base of the robot, a robotic arm is mounted to allow the user to interact with the environment. The arm was chosen to be a KUKA LWR 4+, where LWR stands for Light Weight Robot. It is a LWR robot since it is only 16 kg while still being able to handle a 7 kg load. Furthermore, the arm has 7 degrees of freedom (DOF) and the working envelope of the arm has a volume of $1.84m^3$ (KUKA, 2012).

2.2.3 Reflex Takktile

At the end of the KUKA LWR robotic arm, a robotic hand is mounted. This hand is a ReFlex TakkTile and is visible in Figure 2.2. ReFlex Takktile has three fingers which contain 9 pressure sensors each. The hand is underactuated which means that it has a lower number of actuators than DOF (RightHandRobotics, 2017).
In the context of this assignment it is important that pressure sensor values can be obtained from the ReFlex Takktile to determine if an object is touched/grabbed. Furthermore, the actuators of the finger should be controlled as well. There are different control modes available on the ReFlex TakkTile. It is possible to use position, velocity and force control (RightHandRobotics, 2016).

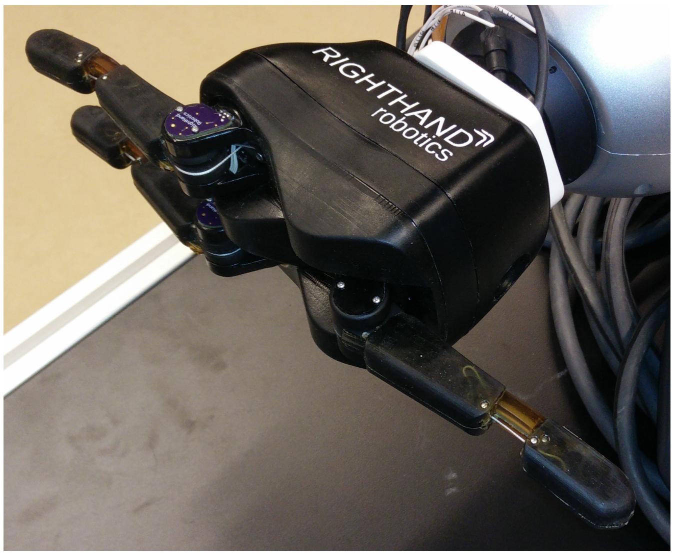


Figure 2.2: The ReFlex TakkTile

Figure 2.3 gives an overview of the layout of the ReFlex Takktile. There are three fingers on the hand labeled from 0 to 2. Each finger consist out of a proximal phalanx and a distal phalanx. Pressure sensor are placed inside those phalanges, labeled from 0 to 8. Pressure sensor 8 is placed at the tip of the finger. Every finger is driven by a motor and are also labeled from 0 to 2.

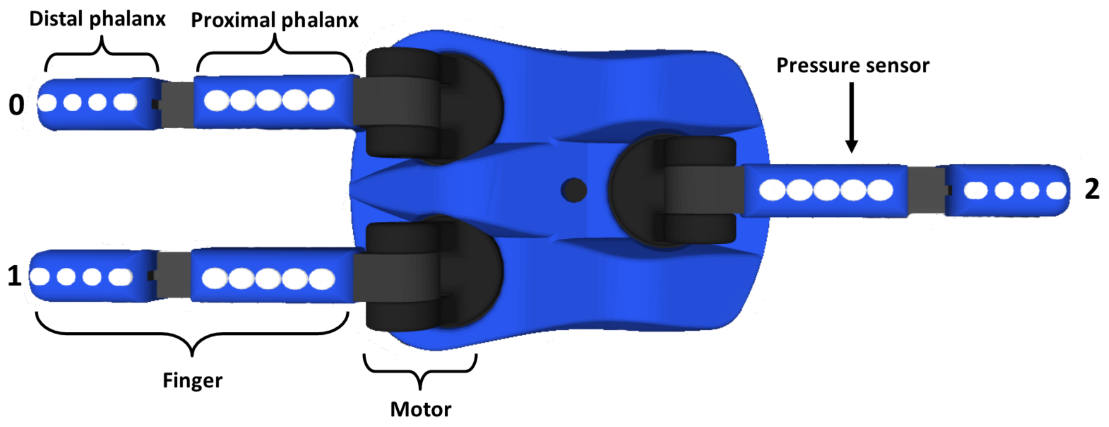
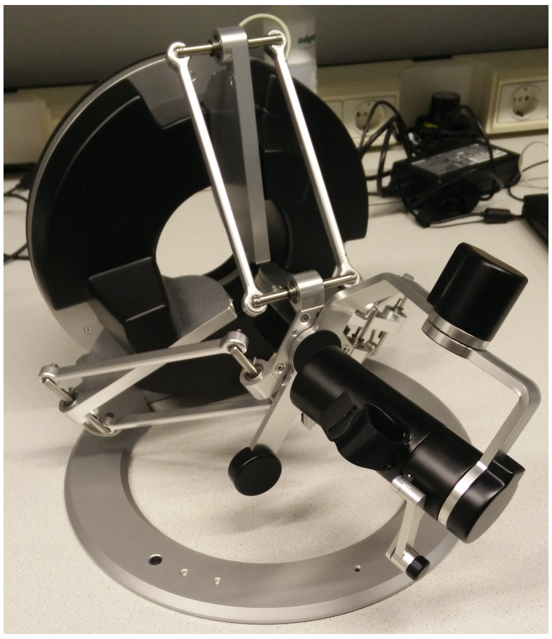


Figure 2.3: Layout of the ReFlex TakkTile

2.3 Omega 7 haptic device

To be able to control the robot from a distance, a Force Dimension Omega 7 is used. A total overview of this system is depicted in Figure 2.4a. The Omega 7 system is a 7 DOF control unit which is capable of providing haptic feedback. Three DOF are reserved for translation, three other DOF are used for rotation and one DOF is used for the gripper. This last degrees of freedom will be of importance during this thesis, because it will allow the user to control the ReFlex TakkTile. The gripper can be seen in Figure 2.4b. The workspace of the gripper is 25mm with a resolution of 0.006mm. Furthermore, it is able to provide forces up to 8 Newton in either direction. Also, the Omega 7 has active gravity compensation to prevent user fatigue (ForceDimension, 2017).


(a) The total Omega 7 system

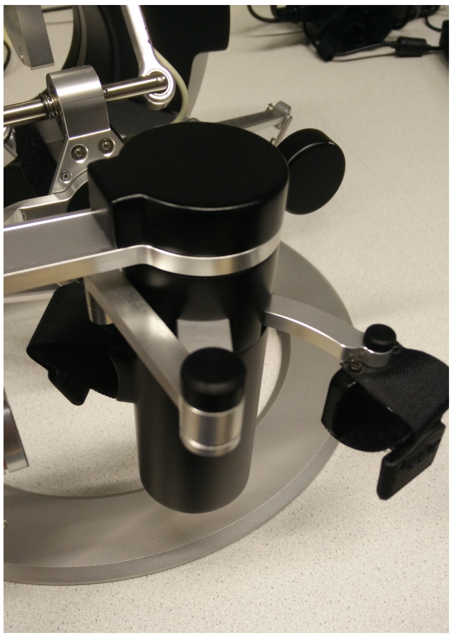

(b) The gripper of the Omega 7

Figure 2.4: The Omega 7 haptic device

3 Requirements

This section gives an quick overview of the requirements of the system. It also shows the importance of every aspect of the system by means of a MoSCoW.

3.1 System requirements

Since this thesis is design oriented, it can be seen as applied research. The following system requirements can be seen as a starting point for the design.

1. The user should be able to control the speed or force of grasping
2. The Omega 7 should give force feedback when there is interaction with the environment
3. The haptic interface should work via a wireless data link
4. The three fingers of the ReFlex TakkTile should be controlled by one gripping action of the Omega 7
5. The fingers of the ReFlex TakkTile should wrap around an object
6. The grasping execution time should not disturb the user

Most of these requirements follow from the perspective of the user. That is, the user should be in control in all times. Furthermore, the haptic response of the interface should be an immersive experience to the user.

3.2 MoSCoW

Following from the system requirements, a MoSCoW table is constructed. Table 3.1 indicates the importance every aspect of the system under design. The numbers between brackets in correspond to the system requirements of Subsection 3.1. The last row of Table 3.1 does not correspond with any of the systems requirements since this is a 'Won't' condition. The rotational actuator inside the ReFlex TakkTile will not be used in the system under design.

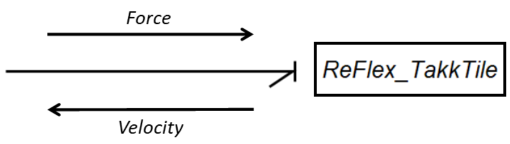
Table 3.1: MoSCoW for system under design

Must
Allow the user to determine the speed or force of grapsing (1)
Give force feedback on interaction with the environment (2)
Be controlled via a direct data link (3)
Control all fingers of the ReFlex TakkTile with one gripping action (4)
Should
Wrap fingers of the ReFlex TakkTile around object (5)
Be controlled via a wireless data link (3)
Won't
Use the fourth actuator in the ReFlex TakkTile (rotational)

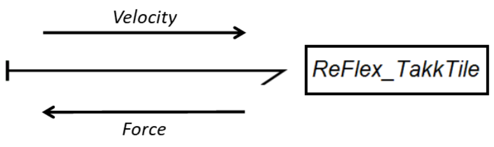
4 Analysis

4.1 Haptic feedback interface

The Reflex TakkTile and the Omega 7 both can be seen as energy ports which can exchange energy with the user and the environment respectively. Figure 4.1a and 4.1b give two possible causality assignments for the ReFlex TakkTile when bond graphs are applied. With effort-in causality, the ReFlex TakkTile receives a force to drive the actuators. This will result in a velocity(Figure 4.1a). This is called an impedance type approach. The inverse is also possible, i.e. receiving a velocity and having a force as an output (Figure 4.1b). This is called an admittance type approach.



(a) Impedance type approach



(b) Admittance type approach

Figure 4.1: Impedance and admittance type approaches

When choosing between an impedance or admittance type approach, there are two important considerations. One of them is the suitability of the device. For example, it is important to examine if the ReFlex TakkTile is able to be driven by force control and/or velocity control. The same holds for the ability to read out the force and/or velocity from the ReFlex TakkTile. Another consideration is the environment the device will encounter. Namely, if the environment the device will encounter be soft or stiff.

The impedance type approach provides very good performance when the environment is stiff but results in poor accuracy when the environment is soft (Ott et al., 2010). Impedance type devices that work well in impedance mode have low inertia, low friction and are back-drivable. Due to their design, force control can be achieved trough current control of the motors. The Omega 7 is best suited for the impedance type approach (Hou et al., 2014).
On the other hand, the admittance type approach provides very good performance for soft environments but results in contact instability for stiff environments. Admittance type devices have high inertia, high friction and are not back-drivable (Ott et al., 2010). These devices operate in a velocity controlled mode to allow velocity-in causality and use force sensors to measure and return the force.

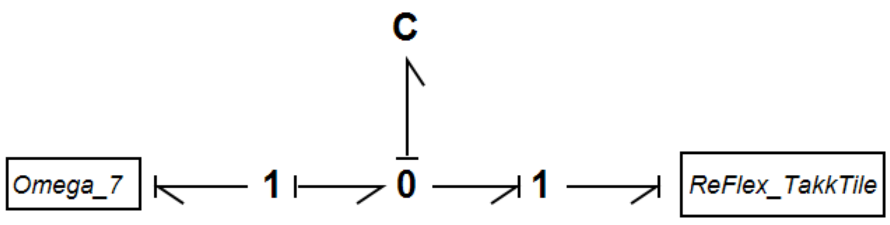
It is important to see if it is actually possible to actuate the ReFlex TakkTile and Omega 7 with a force or velocity as input and if it feasible to obtain the velocity and force. Table 4.1 gives an overview of the possible inputs and outputs of the ReFlex TakkTile and the Omega 7. From the table it is clear that both approaches can be used for the ReFlex Takktile. The Omega 7 only allows for force control as an input so only the impedance type approach can be used.

Table 4.1: Inputs and outputs of the ReFlex TakkTile and Omega 7 (RightHandRobotics, 2016)

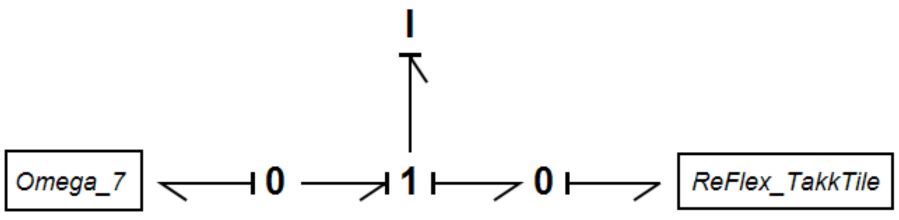
	ReFlex TakkTile	**Omega 7 (gripper)**
Inputs:	Position control Velocity control Rough force control	Force control
Outputs:	Pressure sensors Velocity measurement Position measurement	Position measurement Velocity measurement

An important aspect to note is that the actuators need to be driven inside the ReFlex TakkTile and the Omega 7. These actuators need a force/torque input, so a position/velocity cannot simply be dictated. In case of position and velocity control, control loops are applied to allow position/velocity input based on which force on the actuators is calculated. These control loops run on the hardware itself.

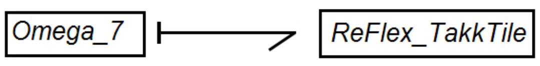
When it comes to the haptic interface between two devices, there are 4 possibilities based on their causality. These are depicted in Figure 4.2. The most ’easy’ approaches would be either Direct 1 or Direct 2. With these approaches the ReFlex TakkTile and Omega 7 have opposite causalities, so they can be connected directly. It would be harder to connect them if they have the same causality on either side. This would require a impedance or admittance control structure, depicted in Figure 4.2a and 4.2b respectively.



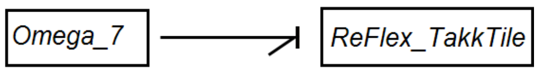
(a) Impedance haptic interface approach



(b) Admittance haptic interface approach



(c) Direct 1 approach



(d) Direct 2 approach

Figure 4.2: Control type approaches

Table 4.2 gives a total overview of the possible haptic interfaces. The choice on which type of haptic interface is suitable for this thesis depends on the two sides of the interface and if they can best be used in impedance or admittance mode i.e. effort-in or flow-in.

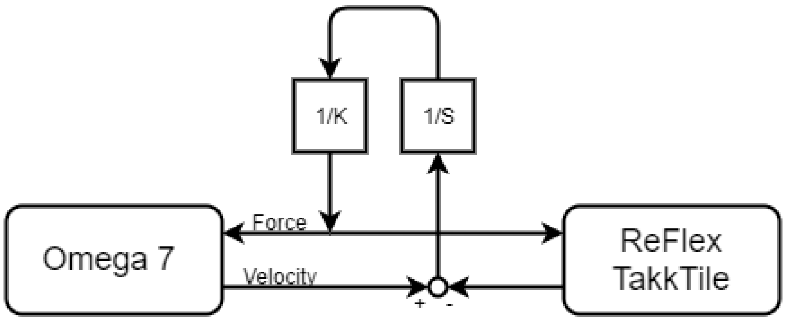
Table 4.2: Types of control

ReFlex TakkTile / **Omega 7**	*effort-in*	*flow-in*
effort-in	Impedance control	Direct 1
flow-in	Direct 2	Admittance control

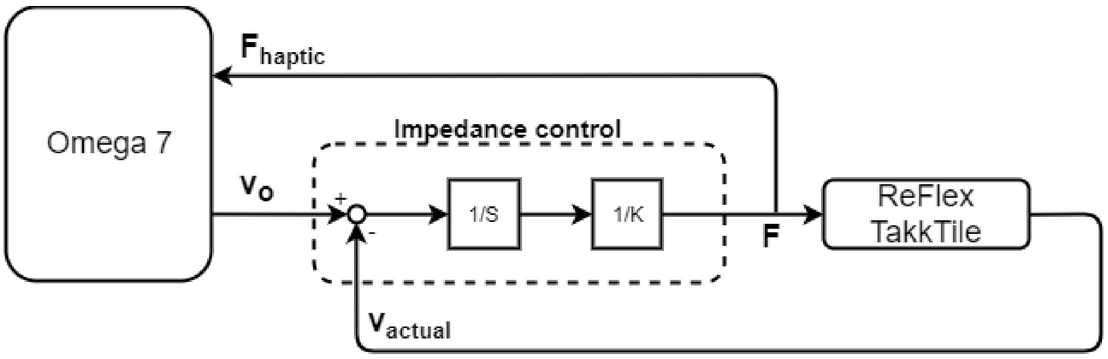
The Omega 7 is an impedance type device and is therefore an effort-in type device. This results in two remaining types of haptic interfaces. When looking at the environment, the ReFlex is most likely to encounter stiff objects. From this perspective, the ReFlex should be treated as an effort-in type device and that it should be impedance controlled (Ott et al., 2010). However, the Direct 1 approach might work better since the mechanical design of the ReFlex TakkTile makes it more suitable to be treated as an admittance type device. The pressure sensors can be used to obtain a measure of force. (RightHandRobotics, 2016).

4.2 Control schemes

The resulting haptic interfaces, impedance control and direct 1 control, can be converted to control schemes. To do this, the bond graphs can be converted to signal graphs. The impedance type interface in Figure 4.2a is converted to a signal graph in Figure 4.3a, or, equivalently, the control scheme in Figure 4.3b. When the user interacts with the Omega 7, they are dictating a velocity(V_0). The force(F) that is send to ReFlex is computed from the difference between the reference velocity(V_0) and the actual velocity of the fingers(V_{actual}). The force that is send to the ReFlex is also used as force feedback to the user(F_{haptic}).



(a) Impedance interface approach signal flow graph



(b) Impedance control (Soares, 2014)

Figure 4.3: Impedance type control

The second control scheme which can be used is the direct control approach. The direct 1 type interface in Figure 4.2c is converted to a signal graph in Figure 4.4. Since the Omega 7 and the ReFlex TakkTile have opposite causalities, the control structure is less complex. The velocity from the gripper can be directly mapped to a velocity for the fingers of the ReFlex and the data from the pressure sensors of the fingers can be used to calculate the force feedback for the gripper.

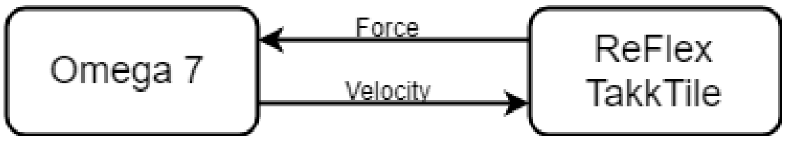


Figure 4.4: Direct control approach

Since, the ReFlex TakkTile has velocity and force control, either effort-in or flow-in could be used. Some early tests showed that the force controller available in the ReFlex TakkTile is not suitable for this type of control. Therefore, the direct 1 approach was adapted. The final choice of the control type is based on the actual behaviour of the ReFlex.

5 Design & implementation

For the design, there are two major parts which will be discussed in the following subsections; how the control structure is implemented and how the software is structured.

5.1 Control structure

The control structure that was implemented is the direct control structure. It is shown in Figure 5.1. Between the Omega 7 and the ReFlex TakkTile mapping is included to convert the single DOF of the gripper to the multi-DOF fingers of the ReFlex. Furthermore, mapping is included to convert the pressure sensor data to force feedback for the user. A clear difference is the shift from velocity control to position control. During early test, the ReFlex behaved much more consistently when driven by position control. Equation 5.1 and Equation 5.2 show position control and velocity control respectively. These equations show that intrinsically, these approaches are the same. Since the position control behaved better, this change was made in the control structure.

$$F_{pos} = K_P \cdot x + K_D \cdot \dot{x} \tag{5.1}$$

$$F_{vel} = K_P \int v + K_D \cdot v \tag{5.2}$$

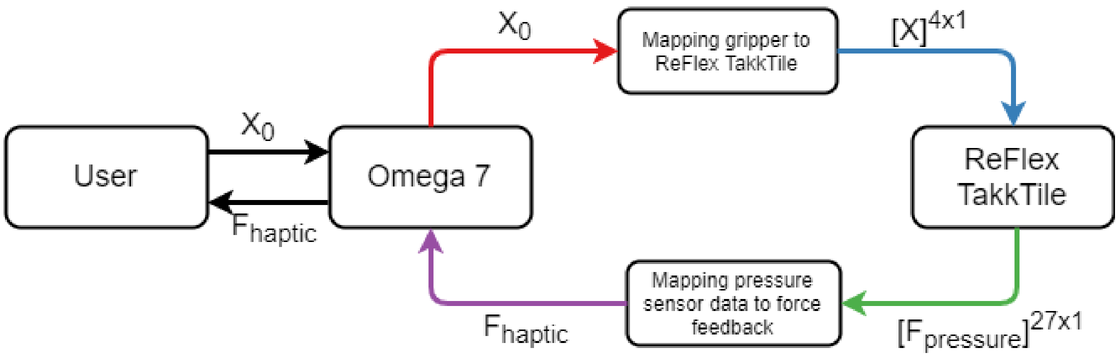


Figure 5.1: Control scheme for the haptic interface

5.1.1 Mapping gripper to ReFlex TakkTile

The gripper of the Omega 7 only has one degrees of freedom, in the gripping action, and the ReFlex TakkTile has four degrees of freedom. Therefore, mapping has to be included to convert the position of the gripper of the Omega 7 to a position for the fingers of the ReFlex. This mapping is chosen to be linear. That is, the position of the gripper is directly mapping to the position of the fingers. Every finger of the ReFlex receives the same position. The ReFlex has internal position control to drive the motors of the fingers. Furthermore, the ReFlex has a 4th degrees of freedom to rotate 2 out of 3 fingers. This DOF is omitted for now and the default configuration, as seen in Figure 5.2, is used instead.

5.1.2 Mapping pressure sensor data to force feedback

The pressure data from the sensors should also be mapped back to force feedback for the gripper. The initial approach was to directly map the data from the pressure sensors to force feedback for the gripper of the Omega 7. However, by using this approach, the user also received force feedback when moving the fingers of the ReFlex away from the object. Combined with the delayed mapping from the gripper of the Omega 7 to the fingers of the ReFlex, this resulted in an unnatural response. All in all, the response of the interface was not satisfactory using the direct force mapping from the pressure sensors of the ReFlex to the Omega 7. Therefore, an alternate approach was used to overcome this problem.
Since there are 27 force sensors in the hand, averaging is used to reduce the complexity of the problem. The data coming from 4 pressure sensors in a distal phalanx and 5 pressure sensors from a proximal phalanx are averaged. Since the contact area of every phalanx is small compared to the total size of the ReFlex and the ReFlex is most likely to encounter large objects, it is assumed that averaging these values is acceptable. In this way, the 27 force sensor values are converted to 6 averaged values. These 6 values correspond to the 6 phalanges of the ReFlex.
The interface decides if the fingers touch an object by means of a force threshold. Every phalanx with its corresponding averaged value from the pressure sensors is compared to the force threshold. If the threshold is crossed, the current position of the gripper of the Omega 7 is saved as a reference. This is done to increase the stability of the system. The stability increases because the force feedback is not dependent on position of the fingers anymore. By means of Hooke's law (Equation 5.3), the force feedback is determined. The stiffness factor is determined empirically and in such a way that it works best with stiff environments.

$$F = -K(x - x_{ref}) \tag{5.3}$$

The check for the threshold crossing and calculating the force feedback is done for every finger. This means that every finger has its own virtual spring and reference position. This results in 3 force feedback values corresponding to the fingers of the ReFlex. To convert these 3 force feedback values to a single force feedback for the gripper of the Omega 7, a weighted average is used. This weighted average is based on the configuration of the fingers of the ReFlex as shown in Figure 5.2. Since there are two fingers on one side and there is one finger on the other side, it was chosen to use a $\frac{1}{4}, \frac{1}{4}, \frac{1}{2}$ weighted average respectively. This corresponds to the assumption that the forces from finger 0 and 1 should add up to the force from finger two. It is assumed that the object is a rest and the fingers grasp the object completely. In the end, the mapped force feedback is exerted on the gripper of the Omega 7.

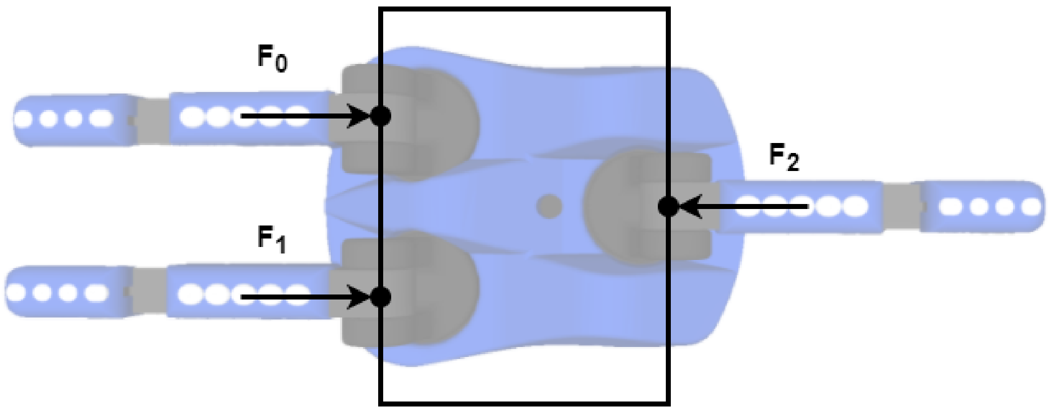


Figure 5.2: Forces applied on objects by the fingers of the ReFlex TakkTile. The black box represents an object and the force vectors mark the points where the fingers apply pressure.

5.2 Implementation

This subsection gives and overview of the software implementation. Besides the implementation of the control structure, other important aspects, which influenced the final product, are explained. The implemented software can be found in Appendix A.

5.2.1 Structure

Figure 5.3 shows the structure of the software in ROS. The software implementation sits right between the ReFlex TakkTile and the Omega 7 as its own node. To obtain the data from the Omega 7, the interface uses the functions in the header file of the Omega 7. The header file of the Omega 7 is included in the main file of the interface. By using this method, the position of the gripper is obtained directly and the force feedback is set directly as well by using the functions from the header file. The interface communicates via topics with the ReFlex to obtain the force sensor values and to command the position of the hand.

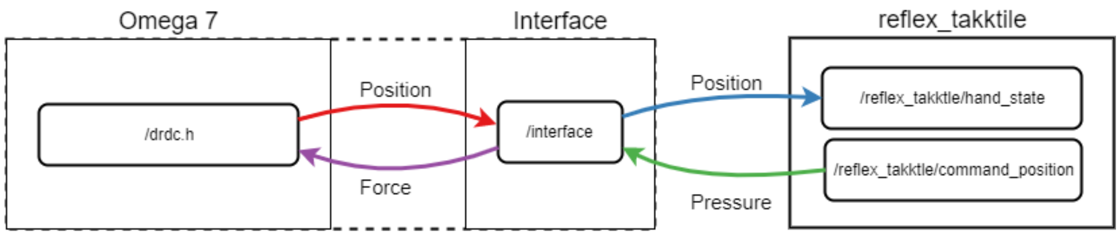


Figure 5.3: Structure of the program

5.2.2 Refresh rate

During early tests, it came clear that the ReFlex was not able to follow the position of the gripper fast enough. To find a explanation for this, the ROS package of the ReFlex was further examined. In this package, the driver node can be found. Three hard coded time delays can be found inside the function which drives the motors. All these time delays add up to 0.09 seconds. According to the documentation, these time delays are needed to prevent the brain board of the ReFlex from freezing. Therefore, the refresh rate of the program was adjusted to account for these internal delays. A rate of 15 Hz seemed to provide a good response.

5.2.3 Initialisation procedure

The startup of the interface requires the initialization of nodes, publishers and subscribers. Furthermore, it detects the Omega 7 and initializes it. The ReFlex is calibrated using the services of the ReFlex node. The initialization of the Omega 7 is designed in such a way that the user can insert his/her finger in the gripper without the actuation of the ReFlex TakkTile. This is achieved by applying a force on the gripper to close it. If the user counters this force by moving his/her finger outward, the program starts. In this way, the position of the gripper matches the open position of the ReFlex. Figure 5.4 gives an overview of the total initialisation procedure.

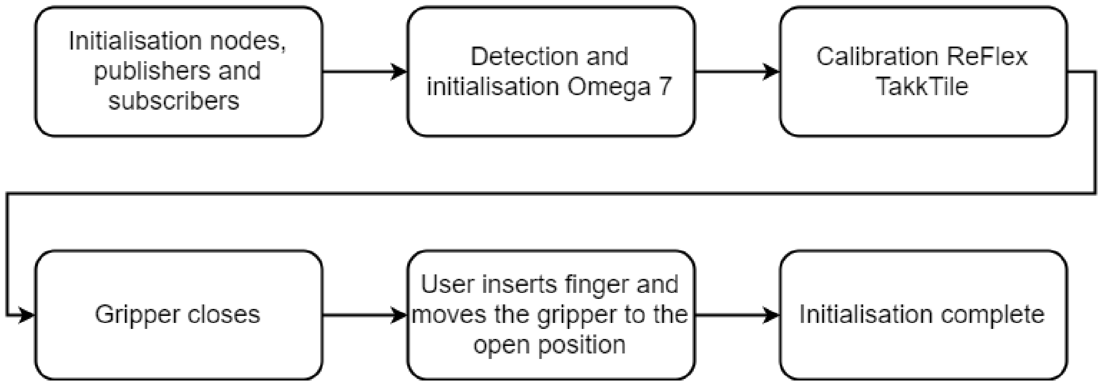

Initialisation nodes, publishers and subscribers
Detection and initialisation Omega 7
Calibration ReFlex TakkTile
Gripper closes
User inserts finger and moves the gripper to the open position
Initialisation complete

Figure 5.4: Overview of the initialisation procedure

5.2.4 Mapping gripper to ReFlex TakkTile

The first part of the interface is the mapping of the position of the gripper to a position for the fingers. The gripper is able to move between 0 and 0.027 meter and the fingers of the ReFlex can move between 0 and 3.4 radians (≈195 degrees). The mapping is done linearly and inversely since the open position of the gripper is 0.027 meter and the open position of the ReFlex is 0 radians.

5.2.5 Mapping pressure sensor data to force feedback

The second part of the interface is the mapping of the sensor values from the pressure sensor to useful force feedback for the gripper of the Omega 7. Figure 5.5 gives an overview of the mapping process for the force feedback.
At the start of the mapping process, a distinction is made between the distal and proximal phalanx of a finger. If the distal phalanx of the finger passes the force threshold first, then only the averaged pressure sensor value from this phalanx contributes to the force feedback. The same holds for the proximal phalanx. Then a reference position of the gripper of the Omega 7 is saved. This is also done for every finger. By using Hooke's law from Equation 5.3, the force feedback from every finger is calculated.
However, if the distal phalanx passes the force threshold *after* the proximal phalanx, both phalanges contribute to the force feedback. This is achieved by scaling the stiffness factor of Equation 5.3. This gives the impression of a tighter grip. By using this method a distinction is made between a pinch and a full grasp.
The procedure described above is done for every finger, in every iterations of the program. The force feedback deducted from every finger is then averaged again by using the weighted average. The resulting force feedback is send to the gripper of the Omega 7. When the position of the gripper passes the reference position of a finger, the force feedback is disabled for this finger.

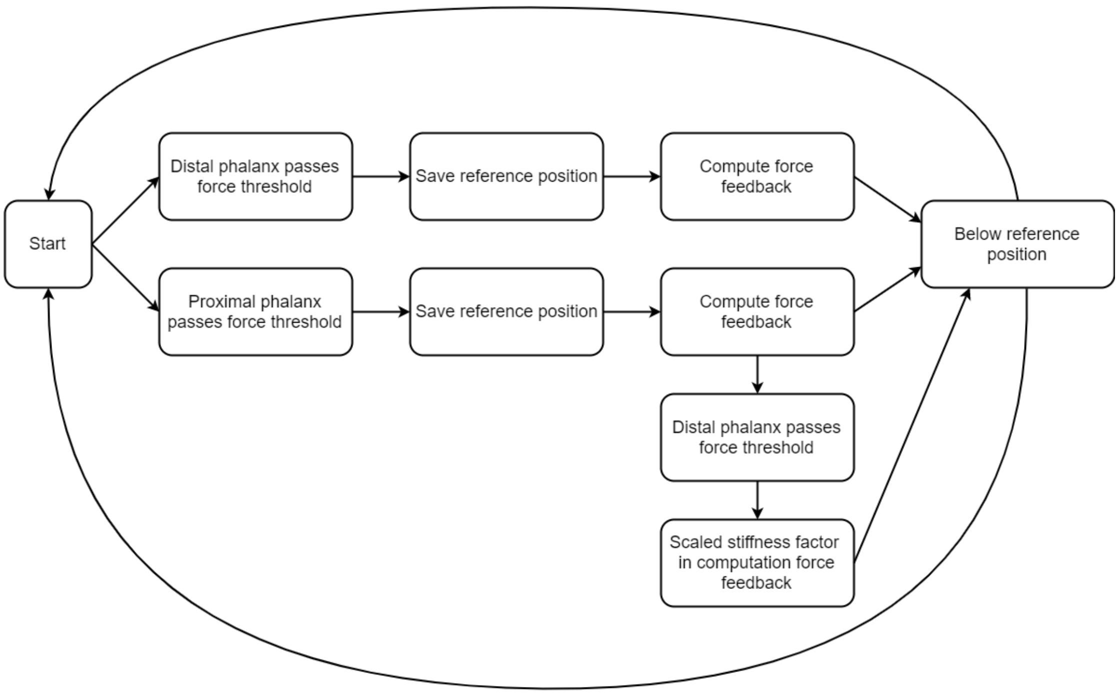
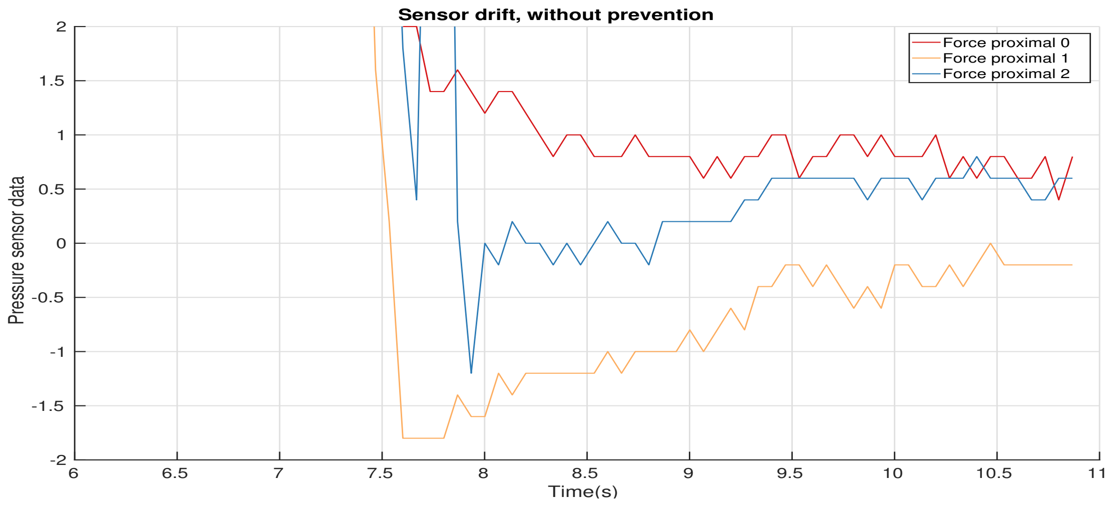

Start
Distal phalanx passes force threshold
Save reference position
Compute force feedback
Proximal phalanx passes force threshold
Save reference position
Compute force feedback
Below reference position
Distal phalanx passes force threshold
Scaled stiffness factor in computation force feedback

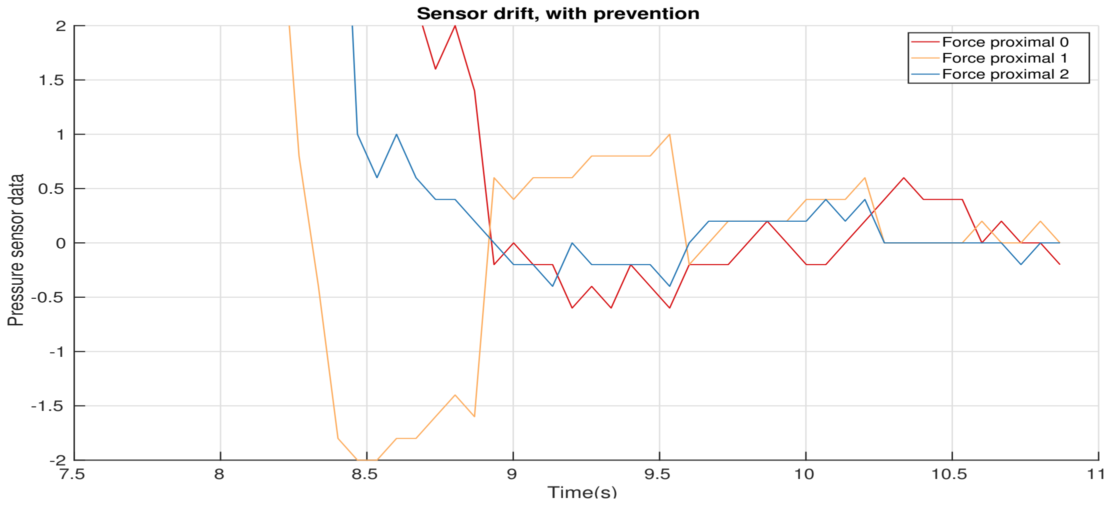
Figure 5.5: Overview of the mapping process for force feedback

5.2.6 Drift prevention

Furthermore, it was found that when interacting with an object, the values from the pressure sensors start to drift. Figure 5.6a shows the drift phenomena of the pressure sensors. When the object is released at t=7.5, the sensor values do not return to zero due to drift. To overcome this problem, the pressure sensors of the ReFlex TakkTile are re-calibrated. The re-calibration is done when the pressure sensor values are below the force threshold. This is done to make sure that the fingers are not touching an object when re-calibrating. Figure 5.6b shows the sensor drift with prevention. After t=8.3, the sensor values return to zero every 20 iterations of the program.



(a) Drift of the pressure sensors, without drift prevention



(b) Drift of the pressure sensors, with drift prevention

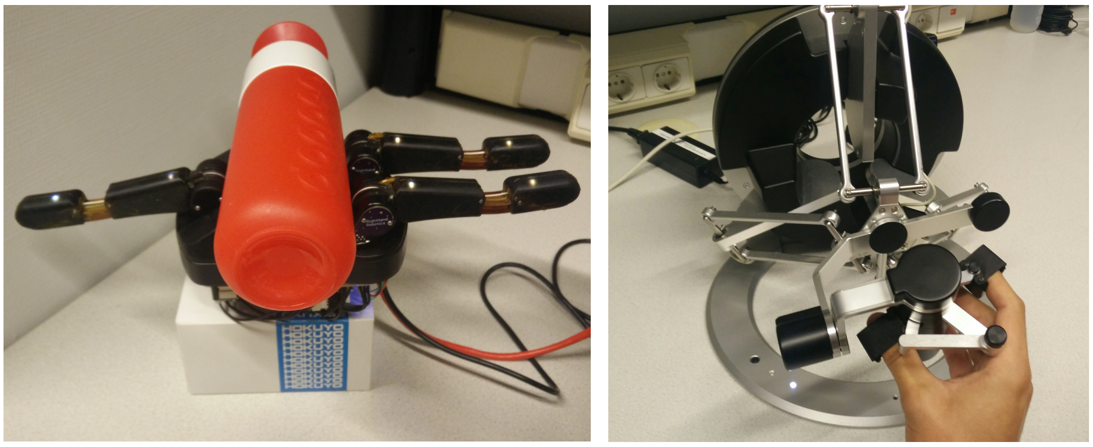
Figure 5.6: Sensor drift, without and with prevention

6 Results

This section will show the testing setup and how the results are obtained. Different testing situations are created to test the system.

6.1 Testing setup

Figure 6.1a shows the testing setup for the ReFlex TakkTile. The hand is removed from the robotic arm to make testing more convenient. The ReFlex is placed on top of a small box to still be able to connect the power cord and the ethernet cable. To test the setup, a hard plastic bottle was used. To account for smaller objects, a computer mouse was used. The Omega 7 was used just as it is. Figure 6.1b shows the position of the user in the gripper of the Omega 7. Both sides of the interface were connected to a laptop.



(a) The testing setup for the ReFlex TakkTile **(b)** The testing setup for the Omega 7

Figure 6.1: The testing setups

6.2 Results

The various plots in this subsection are produced using the bagfile functionality of ROS. The data of the bagfiles is processed using MATLAB.

Mapped finger position and encoder data

This test was conducted to test the ability of the ReFlex to follow the commanded input. The result from this test is visible in Figure 6.2. In this test, the fingers of the ReFlex were first closed and then opened again. The closing part of the fingers was executed in a slow manner, while the opening part was executed fast. From the plot it is clear that the ReFlex is able to follow the input well during slow execution. The difference does not exceed 0.5 rad in this phase. The fast execution phase shows a larger difference in position. The maximum difference there is -1.4 rad.
Furthermore, the ReFlex needs time to reach the commanded position. When the ReFlex is moving slow it takes on average 0.2 seconds to reach the desired position. This appears to be a constant delay. However, when moving fast, this time can increases to 0.5 seconds. This is observed in Figure 6.2 between t=6 and t=7. This is noticeable to the user and is due to the internal time delays of the driver of the motors in the ReFlex as discussed in Section 5. Also the internal position control is assumed to be part of this delay.

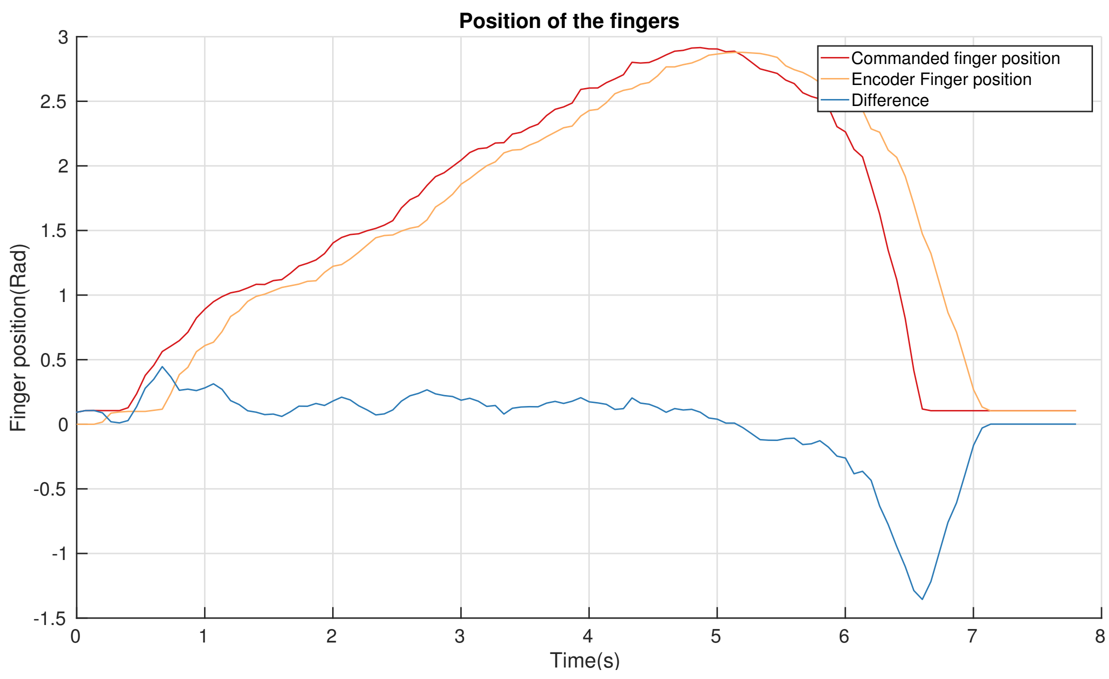


Figure 6.2: Commanded position and actual position of the ReFlex TakkTile fingers

Contact dectection

This test was conducted to test the contact detection. The result is visible in Figure 6.3. During this test, a full grasp was executed. Only the averaged sensor data from the fingers is plotted to avoid having too much lines in one single plot. The vertical black lines indicate the first contact of the proximal and distal phalanges respectively. The release of the object is marked with a vertical black line as well. The dashed horizontal line represents the force threshold. If this threshold is crossed, contact is detected. Furthermore, there are negative pressure sensor reading around 6.5 seconds. The cause for this is unknown, but it might be caused by the drift of the sensor as mentioned in Section 5. Due to the implemented re-calibration of the pressure sensors, this value returns to zero again.

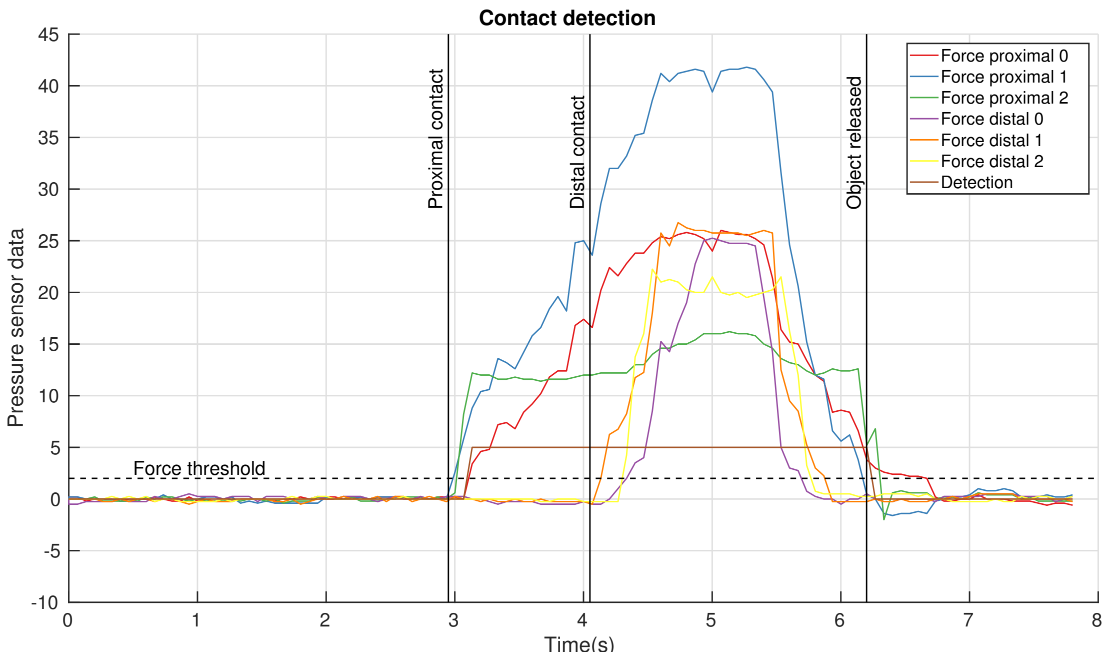


Figure 6.3: Contact dectection

Omega position, finger positions and force feedback

This test was executed to verify the functionality of the total system. The result of this test is visible in Figure 6.4. This is the same test as the force mapping test. This means that the same bagfile was used during the processing in MATLAB. Again, the black lines indicate the first contact of the proximal and distal phalanges. The haptic interface shows correct behaviour. This means that the force feedback starts when an object is hit and it stops directly when the object is released.

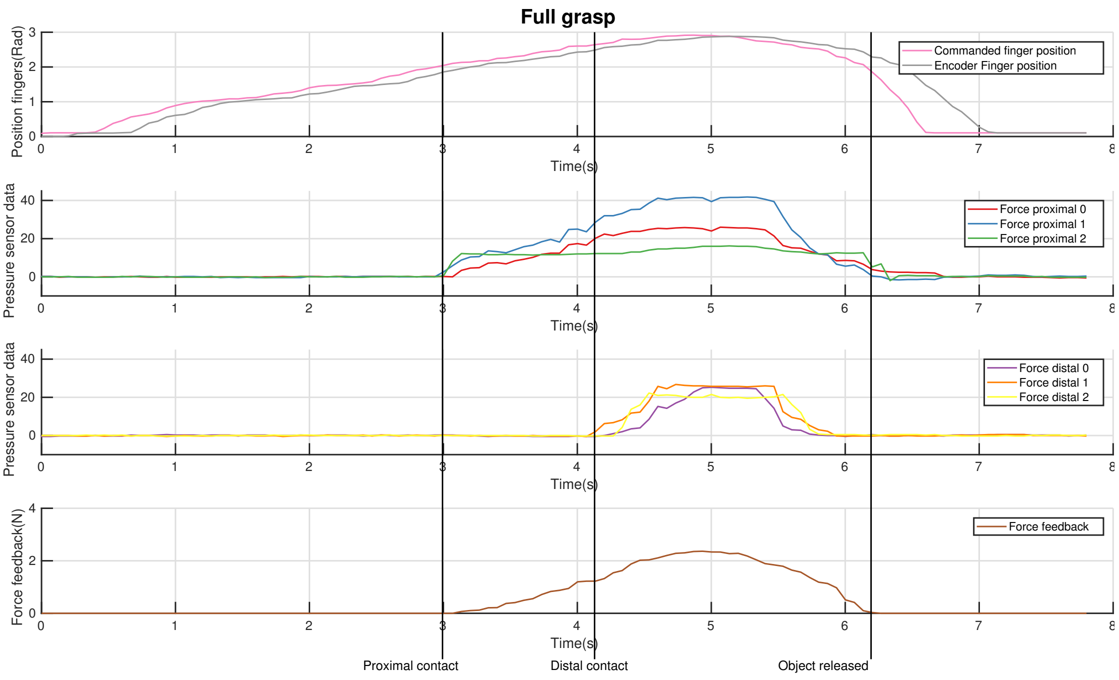


Figure 6.4: Total system functionality

Partial & full grasp

This test was executed to test the difference between a partial grasp and a full grasp. A partial grasp means that only 2 fingers of the ReFlex are used when grabbing an object. The result of this test is visible in Figure 6.5. The first part of the graph corresponds to a partial grasp and the second part to a full grasp. In the first part, the lines of the proximal phalanx 1 and distal phalanx 1 register no pressure. This corresponds to the conducted test where only finger 0 and 2 were used to grab the object. When only 2 fingers are used, the difference in force feedback is clear compared to a full grasp. That is, less force feedback is send to the user. In the second part, the object is grabbed, released and then grabbed again quickly. This explains the two bumps in second part of the graph.

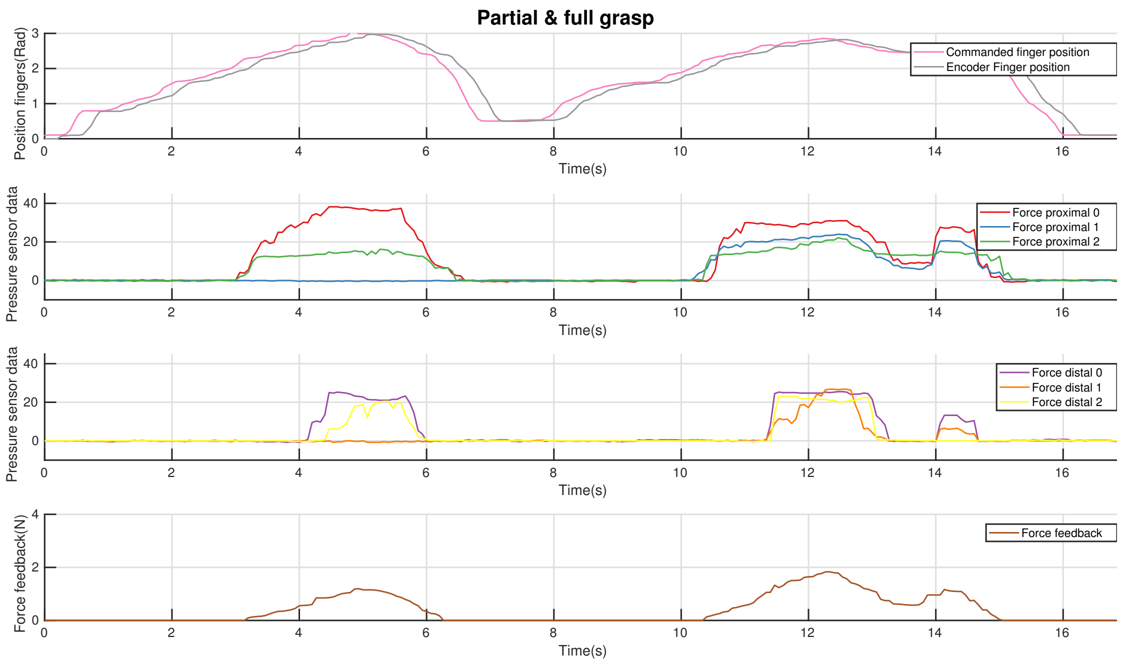


Figure 6.5: Partial grasp and full grasp

Pinched grasp

This test was executed to test the pinched grasp functionality. When executing a pinched grasp, only the tip of the fingers are used. The result of this test is visible in Figure 6.6. The position of the gripper of the Omega 7 is also plotted to show that the gripper to position mapping function properly. The closed position of the gripper corresponds to the open position of the hand. Therefore, the position of the gripper shows inverse bahaviour compared to the mapped position for the ReFlex. Furthermore, the haptic interface shows correct behaviour again. This means that the force feedback to the user is also significantly less (<1N). Since this is a pinched grasp, the sensor data from the proximal phalanges stays low. A thing to note is a decrease in the sensor values from finger 2 around 6.5 seconds. At that point, finger 2 released the object for a short period of time.

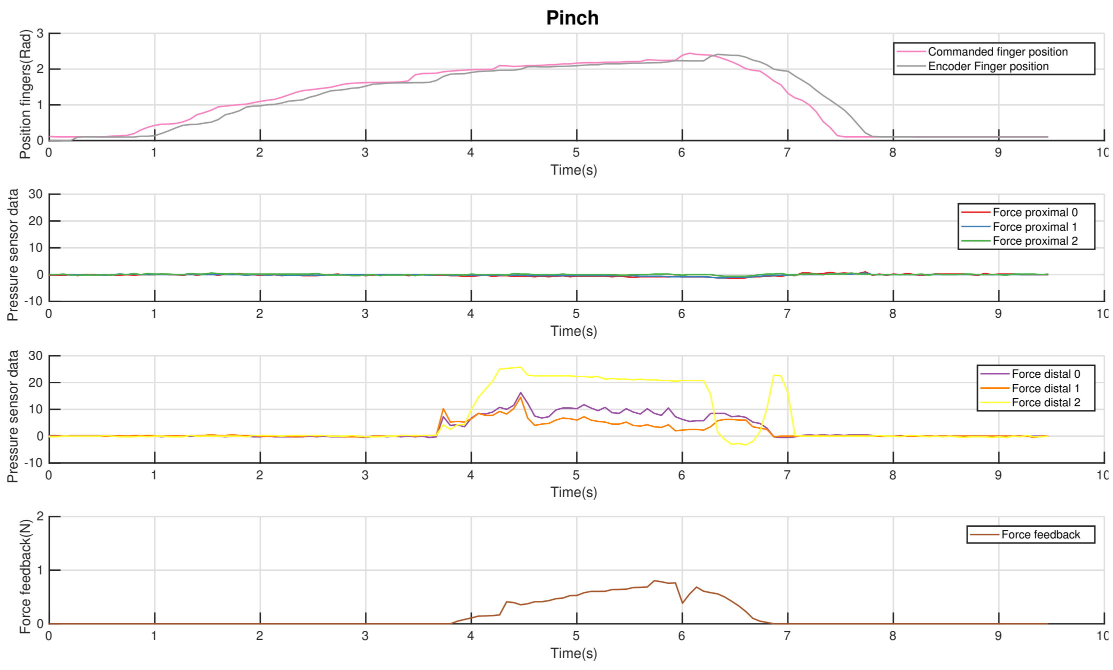


Figure 6.6: Pinched grasp

Different objects

The final test that was executed to show the difference between two different sized objects that are grabbed. The result of this test is visible in Figure 6.7. In the first part of the graph the same bottle was grasped as in the other experiments. In the second part, a small computer mouse was used. The haptic interface shows correct behaviour again. In the second part of the graph, the sensor data from the distal phalanges stays low, because the object is too small to be grabbed by the tip of the fingers. This also resulted in less force feedback compared to the first part of the graph.

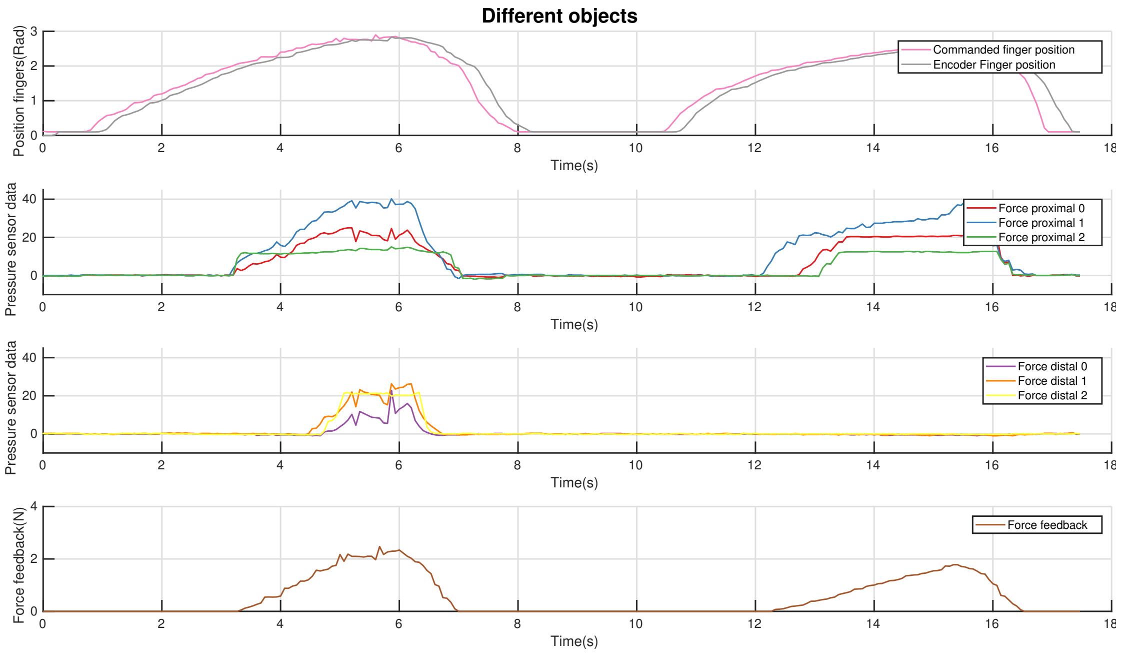


Figure 6.7: Different objects

7 Discussion

The performed tests are discussed in this section.

7.1 Position ReFlex TakkTile

The first test was executed to test the ability of the ReFlex TakkTile to follow the commanded input position from the user. From this test is was clear that time delays were occuring. This ranged from 0.2 to 0.5 seconds and is depended on the speed of movement from the user. When moving slow, this delay is still acceptable and the user is able to receive accurate feedback. However, during fast movement, the position of the ReFlex does not match the position of the gripper anymore. This means that the user may receive force feedback too late. If the mapped position from the gripper of the Omega 7 to the fingers of the ReFlex results in an object being touched, it should result in force feedback. However, since there is position delay, the fingers are not touching the object yet. This means that pressure sensors do not register pressure and no force feedback is exerted on the gripper yet. This position delay is an essential part of the haptic interface and therefore affects the functionality of it.

A cause for the excessive delay in the fast movement phase might be that the dynamixel motors of the ReFlex Takktile have a maximum velocity. It is found that the motors receive a command between 0 and 1023 from the driver. Where 0 means no movement and 1023 means maximum velocity. This command is based on the desired speed for the motors, the gear ratio of the motors and a velocity scaling factor. The command for the motors is saturated if the desired velocity command exceeds 1023. The command for the motors is given by equation 7.1.

$$command = v_{desired} \cdot \frac{motor\_to\_joint\_gear\_ratio}{velocity\_scale} \tag{7.1}$$

Where, the *motor_to_joint_gear_ratio* equals 1.42 and the *velocity_scale* equals 0.01194 rad/s. The resulting command is a dimensionless quanity. Since the maximum command equals 1023, this means that the maximum $v_{desired}$ equals approximately 8.6 rad/s. This is the upper limit of the speed of the fingers according to the software of the driver. The actual maximum velocity of the ReFlex TakkTile in the first test was approximately 3.5 rad/s. This is significantly less that the theoretical maximum velocity from the driver. Therefore, the software of the driver is unlikely to be the limiting factor.

The position controller within the driver of the ReFlex might cause the additional delay. Unfortunately, the actual position controller was not found in the driver of the ReFlex.

7.2 Sensor data ReFlex TakkTile

During the tests, some phenomena were observed concerning the pressure sensors inside the fingers of the ReFlex TakkTile. As observed in Figure 6.3, 6.4 and 6.6, negative sensor readings occurred. The cause for these unusual readings is unknown, but it might be caused by the drift of the pressure sensors. This was also discussed in Section 5. While the sensors are re-calibrated when no object is touched, it is still possible for the sensor values to drift when an object is being touched.

7.3 Testing circumstances

During almost all tests, the same object was used. This was done to ensure uniform test results. A stiff object was used, because the robotic system is most likely to encounter stiff environments. However, in some circumstances, soft objects might be present as well. This was not tested and could have an impact on the functionality of the robot.
This also holds for the testing position of the ReFlex TakkTile. The fingers of the ReFlex were facing up during all tests. Other positions such as a vertical or an upside down position might be useful as well.

7.4 Force feedback

In the last three tests in Section 6.2 required the ReFlex TakkTile to grasp objects partially and with a pinched grasp. Also, a smaller object was grasped using only the proximal phalanges of the fingers. In the current implementation, more force feedback is applied if there are more phalanges are touching the object. So, for example, if a pinched grasp occurs, only the distal phalanges of the ReFlex grasp the object. This means that only 3 out of 6 phalanges touch the object. The resulting force feedback - calculated using Hooke's Law - is less compared to a full grasp. However, in comparison to a human hand, the human hand might be able to grasp an object just as firm with a pinched grasp as with a full grasp. The same holds for the partial versus the full grasp and the smaller object versus a large object. Therefore, the resulting force feedback might not correspond to the actual human hand behaviour. This is something that could be changed regarding the current implementation of the force feedback.

8 Conclusion

The goal of this assignment was to create an haptic interface between a ReFlex TakkTile and an Omega 7 haptic device. Several approaches have been examined and based on the hardware specifications, a direct haptic interface was implemented. Due to time delays inside the driver of the ReFlex Takkile, the response of the interface was not satisfactory. Therefore, the direct structure was changed to overcome this issue. This resulted in a stable interface.
Tests were executed to test the functionality of the interface. From this, it was clear that the interface is best suited for stiff environments and that it functions optimal when the speed of the finger of the ReFlex Takktile is kept low.
Initial requirements were set for the interface in Section 3. All of these requirements were met, except from the grasping execution time. This should not disturb the user. However, when the speed of interaction is high, the interface does not respond adequately due too large time delays in the system.
Likewise, a MoSCoW table was constructed for the system under design. There was a 'Should' present which stated that the interface should be controlled via a wireless link. All the performed tests were wired and this allowed for convenient testing. However, due to time constrains, these tests were not done wirelessly.

9 Recommendations

Based on the conducted research, the following improvements of the setup are recommended.

The system has not been tested in the wireless configuration. In the testing setup, a wired connection was used. Due to time limitations the wireless setup was not tested. However, the current setup has shown promising results and it seems that the interface is able to function in a wireless setup. In the ReFlex TakkTile, a software wrapper takes care of the position control of the robot. As mentioned in Section 5, this introduces time delay. However, the haptic interface responded well and in such a way that the user is not restricted by the movement of the ReFlex compared to the movement of the gripper of the Omega 7. Only when the user uses quick gripping action, delay is noticeable. If the user controls the gripper in a calm manner, the interface has potential to function wireless.

In the current configuration of the interface, the stiffness in Hooke's law - which determines the force feedback - is constant. This means that user cannot distinguish between hard or soft objects. The current haptic interface is more reliable for solid objects. To overcome this problem, the stiffness of the interface must become dependent on the data from the pressure sensors and the position of the fingers. If the fingers cover more distance compared to the measured pressure from the sensors, the ReFlex most likely encounters a soft object. The dual also holds for solid object. Therefore, the stiffness is dependent on the change in force over the change in distance. The real challenge in this implementation lies in the stability, since the ReFlex does need to deal with time delays.

Furthermore, a change in the structure of the software in ROS would be a recommendation. Currently, the header file of the Omega 7 is directly included in the main file of the interface. To make the structure of the code more modular, an additional node should be created. This node should obtain the state of the Omega 7 and publish it on ROS topics. By using this approach, the interface node is completely isolated from the ReFlex TakkTile and Omega 7.

Another recommendations is to further investigate the possibility of an impedance haptic interface approach. Due to the short time period reserved for the implementation phase, a quick shift was made from this impedance approach to a direct approach. While the outcome of the direct approach was successful, it still might be worthwhile to further examine the impedance type interface in more depth.

Finally, the mapping of the multi DOF of the hand to the one DOF of the gripper might be a source of improvement. In the current setup, the data from the distal and proximal phalanx are both averaged. An improvement of this approach would be to design a gripping profile for every phalanx. To would be sensible because the center of a phalanx is more likely to hit an object than the sides of a phalanx. This could be implemented by means of a weighted average. As a result, certain pressure sensors could have more effect on the force feedback than others, resulting in a more natural gripping experience.

Appendix

A Software implementation

```
#include "ros/ros.h"
#include "std_srvs/Empty.h"

#include <stdlib.h>
#include <stdio.h>
#include <iostream>
#include <string>
#include <math.h>

#include <geometry_msgs/Twist.h>
#include <geometry_msgs/Vector3.h>
#include <std_msgs/Float64.h>

#include <reflex_msgs/Hand.h>
#include <reflex_msgs/VelocityCommand.h>
#include <reflex_msgs/PoseCommand.h>
#include <reflex_msgs/ForceCommand.h>

#include "../../omega7/include/drdc.h"
#include "../../omega7/include/dhdc.h"

#define REFRESH_RATE 15 //11-12 according to code of ReFlex, 15
    seems to provide a good response
#define FORCE_THRESHOLD 2.0
#define MAX_GRIPPER_GAP 0.027
#define MAX_JOINT_ANGLE 3.4
#define STIFFNESS 600.0
#define NUM_FINGERS 3
#define NUM_PRESSURE_DISTAL 4
#define NUM_PRESSURE_PROXIMAL 5
#define SCALING 1.2
#define MAX_CNT 10

reflex_msgs::Hand hand;
geometry_msgs::Vector3 actualGripperPose;
geometry_msgs::Vector3 actualGripperForce;
geometry_msgs::Vector3 actualForcePressureDistal;
geometry_msgs::Vector3 actualForcePressureProximal;
geometry_msgs::Vector3 actualFingerPosition;
```

```
geometry_msgs::Vector3 forceFeedback;
reflex_msgs::PoseCommand reflex_pos;
std_srvs::Empty empty;

double actualGripperGap;
double refGripperGap[NUM_FINGERS];
double setForce[NUM_FINGERS];
double averageSetForce;
double forceDistalPhalange[NUM_FINGERS];
double forceProximalPhalange[NUM_FINGERS];
double posFingers;
double weightedAverage[3] = {0.25, 0.25, 0.5};
bool hapticsOn[NUM_FINGERS];
int cnt;

void startupGripper() {
        // startup process for the gripper
        bool quit = false;

        // force is set to -1.0 to close the gripper
        // user can then place his/her finger in the gripper
        dhdSetForceAndTorqueAndGripperForce(0.0, 0.0, 0.0, 0.0,
            0.0, 0.0, -1.0);
        ros::Duration(0.1).sleep();

        // when the user opens the gripper, exit the loop and the
             program starts
        while (!quit && ros::ok()) {
                dhdGetGripperGap(&actualGripperGap);
                if (actualGripperGap > (MAX_GRIPPER_GAP - 0.001))
                     {
                        quit = true;
                }
        }
}

void hand_data(const reflex_msgs::HandConstPtr& data) {
        // obtain data from hand, this is a callback function
            from the subscriber
        hand = *data;
}
```

```
double map(double x, double in_min, double in_max, double out_min
    , double out_max) {
        // simple mapping function, maps input to defined output
            boundaries
        double map = (x - in_min) * (out_max - out_min) / (in_max
             - in_min) + out_min;
        return map;
}

void getPressureDataProximal() {
        // get data from proximal phalanx and average
        // this is done for every finger
        for (int i = 0; i < NUM_FINGERS; i++) {
                double average = 0.0;
                for(int j = 0; j < NUM_PRESSURE_PROXIMAL; j++) {
                        average = average + hand.finger[i].
                            pressure[j];
                }
                forceProximalPhalange[i] = average /
                    NUM_PRESSURE_PROXIMAL;
        }
}

void getPressureDataDistal() {
        // get data from distal phalanx and average
        // this is done for every finger
        for (int i = 0; i < NUM_FINGERS; i++) {
                double average = 0.0;
                for(int j = NUM_PRESSURE_PROXIMAL; j < (
                    NUM_PRESSURE_PROXIMAL + NUM_PRESSURE_DISTAL);
                     j++) {
                        average = average + hand.finger[i].
                            pressure[j];
                }
                forceDistalPhalange[i] = average /
                    NUM_PRESSURE_DISTAL;
        }
}

void reflexControl() {
        // map gripper gap to a position for the fingers
        posFingers = map(actualGripperGap, 0.0, MAX_GRIPPER_GAP,
            MAX_JOINT_ANGLE, 0.0);
```

```
}

void omegaControl() {
        for (int i = 0; i < (NUM_FINGERS - 1); i++) {
                // pinch
                if ((forceProximalPhalange[i] < FORCE_THRESHOLD)
                   && (forceDistalPhalange[i] > FORCE_THRESHOLD))
                    {
                        if (hapticsOn[i] == false) {
                                hapticsOn[i] = true;
                                refGripperGap[i] =
                                    actualGripperGap;
                        } else if (actualGripperGap >
                            refGripperGap[i]) {
                                hapticsOn[i] = false;
                                setForce[i] = 0.0;
                        } else {
                                setForce[i] = -STIFFNESS*(
                                    actualGripperGap -
                                    refGripperGap[i]);
                        }
                // full grasp
                } else if (forceProximalPhalange[i] >
                   FORCE_THRESHOLD) {
                        if (hapticsOn[i] == false) {
                                hapticsOn[i] = true;
                                refGripperGap[i] =
                                    actualGripperGap;
                        } else if (actualGripperGap >
                            refGripperGap[i]) {
                                hapticsOn[i] = false;
                                setForce[i] = 0.0;
                        } else if (forceProximalPhalange[i] >
                            FORCE_THRESHOLD && forceDistalPhalange
                            [i] > FORCE_THRESHOLD) {
                                setForce[i] = -STIFFNESS*(
                                    actualGripperGap -
                                    refGripperGap[i])*SCALING;
                        } else {
                                setForce[i] = -STIFFNESS*(
                                    actualGripperGap -
                                    refGripperGap[i]);
                        }
                // no force
                } else {
                        hapticsOn[i] = false;
                        setForce[i] = 0.0;
                }
        }

        // calculate the total force feedback using a weighted
            average
        averageSetForce = 0.0;
        for(int i = 0; i < (NUM_FINGERS - 1); i++) {
                averageSetForce += weightedAverage[i]*setForce[i
                    ];
        }
}

int main(int argc, char** argv) {
        // start initialization
        std::cout << "␣INITIALIZING␣...␣" << std::endl;

        // initialize node
        ros::init(argc, argv, "interface");
        ros::NodeHandle n;

        // subscriber
        ros::Subscriber hand_state = n.subscribe("reflex_takktile
            /hand_state", 1, &hand_data);

        // publishers
        ros::Publisher pub_pos = n.advertise<reflex_msgs::
            PoseCommand>("reflex_takktile/command_position", 1);

        // publishers testing
        ros::Publisher pub_pos_gripper = n.advertise<
            geometry_msgs::Vector3>("testing/pos_gripper", 1);
        ros::Publisher pub_force_gripper = n.advertise<
            geometry_msgs::Vector3>("testing/force_gripper", 1);
        ros::Publisher pub_force_distal = n.advertise<
            geometry_msgs::Vector3>("testing/force_distal", 1);
        ros::Publisher pub_force_proximal = n.advertise<
            geometry_msgs::Vector3>("testing/force_proximal", 1);
        ros::Publisher pub_finger_pos = n.advertise<geometry_msgs
            ::Vector3>("testing/finger_pos", 1);
```

```
    ros::Publisher pub_force_feedback = n.advertise<
        geometry_msgs::Vector3>("testing/force_feedback", 1);

    // services
    ros::ServiceClient calibrate_fingers = n.serviceClient<
        std_srvs::Empty>("reflex_takktile/calibrate_fingers");
ros::ServiceClient calibrate_tactile = n.serviceClient<
    std_srvs::Empty>("reflex_takktile/calibrate_tactile");

// initialize reflex takktile
    calibrate_fingers.call(empty);
    calibrate_tactile.call(empty);

    // set refresh rate
    ros::Rate r(REFRESH_RATE);

    // required to change asynchronous operation mode
    dhdEnableExpertMode();

    // open the first available device
    if (drdOpen() < 0) {
    printf("error:␣cannot␣open␣device␣(%s)\n",
        dhdErrorGetLastStr());
    dhdSleep(2.0);
    return -1;
    }

    // print out device identifier
    if (!drdIsSupported()) {
    printf("unsupported␣device\n");
    printf("exiting...\n");
    dhdSleep(2.0);
    drdClose();
    return -1;
    }

    // perform auto-initialization
    if (!drdIsInitialized() && drdAutoInit() < 0) {
    printf("error:␣auto-initialization␣failed␣(%s)\n",
        dhdErrorGetLastStr());
    dhdSleep(2.0);
    return -1;
    } else if (drdStart() < 0) {
```

```
printf("error:␣regulation␣thread␣failed␣to␣start␣(%s)\n",
dhdErrorGetLastStr());
dhdSleep(2.0);
return -1;
}

// stop axis control (and leave regulation thread running
    )
drdStop(true);

// gripper initialization
std::cout << "␣PLACE␣HAND␣IN␣GRIPPER␣...␣" << std::endl;
startupGripper();

// end initialization
std::cout << "␣READY␣" << std::endl;

while (ros::ok()) {
        // get data from reflex and omega
        getPressureDataProximal();
        getPressureDataDistal();
        dhdGetGripperGap(&actualGripperGap);

        // plotting
        actualFingerPosition.x = hand.motor[0].
            joint_angle;
        actualFingerPosition.y = hand.motor[1].
            joint_angle;
        actualFingerPosition.z = hand.motor[2].
            joint_angle;
        forceFeedback.x = averageSetForce;
        actualGripperPose.x = actualGripperGap;
        actualGripperForce.x = averageSetForce;
        actualForcePressureDistal.x = forceDistalPhalange
            [0];
        actualForcePressureDistal.y = forceDistalPhalange
            [1];
        actualForcePressureDistal.z = forceDistalPhalange
            [2];
        actualForcePressureProximal.x =
            forceProximalPhalange[0];
        actualForcePressureProximal.y =
            forceProximalPhalange[1];
            actualForcePressureProximal.z =
                forceProximalPhalange[2];
            pub_finger_pos.publish(actualFingerPosition);
            pub_force_feedback.publish(forceFeedback);
            pub_pos_gripper.publish(actualGripperPose);
            pub_force_gripper.publish(actualGripperForce);
            pub_force_distal.publish(
                actualForcePressureDistal);
            pub_force_proximal.publish(
                actualForcePressureProximal);

            // control reflex side
            reflexControl();

            // control omega side
            omegaControl();

            // actuate
            reflex_pos.f1 = posFingers;
            reflex_pos.f2 = posFingers;
            reflex_pos.f3 = posFingers;
            reflex_pos.preshape = 0.0;
        pub_pos.publish(reflex_pos);
            dhdSetForceAndTorqueAndGripperForce(0.0, 0.0,
                0.0, 0.0, 0.0, 0.0, averageSetForce);

            // when the reflex fingers do not register
                pressure, re-calibrate to prevent drift
            if (hapticsOn[0] == false && hapticsOn[1] ==
                false && hapticsOn[2] == false) {
                    cnt++;
                    if (cnt == MAX_CNT) {
                            calibrate_tactile.call(empty);
                            cnt = 0;
                    }
            }

            // spin once and sleep
    ros::spinOnce();
    r.sleep();
    }

    printf("exiting␣application\n");
```

```
            dhdClose();

            return 0;
    }
```

B How to run the setup

The haptic interface can be set up by using the following steps.

1. Power the ReFlex TakkTile and the Omega 7
2. Connect the ReFlex TakkTile to a laptop via an Ethernet connection and the Omega 7 using the USB-cable. If the Omega 7 is not recognized by the laptop, check if the user has access to USB ports. You can write a udev rule to grant all users access to the Omega 7 device.
3. Install the SDK environment for the Omega 7 in your Home folder. Refer to the user manual for further information.
4. Place the ROS packages for the ReFlex TakkTile and Omega 7 in your Catkin workspace.
5. Create an interface package in the Catkin workspace as well and place the code from Appendix A in the src folder. Also make sure the CMake file of the interface is updated to the following:

```
cmake_minimum_required(VERSION 2.8.3)
project(interface)

find_package(catkin REQUIRED COMPONENTS
  roscpp
  rospy
  std_msgs
  message_generation
  geometry_msgs
  kdl_conversions
)

find_package(orocos_kdl)

catkin_package(
   INCLUDE_DIRS include
   CATKIN_DEPENDS message_runtime
)

include_directories(
  ${catkin_INCLUDE_DIRS}
)

add_executable(interface src/interface.cpp)
target_link_libraries(interface ${catkin_LIBRARIES})
target_link_libraries(interface ${catkin_LIBRARIES} ${
    PROJECT_SOURCE_DIR}/lib/release/lin-x86_64-gcc/libdhd.a $
    {PROJECT_SOURCE_DIR}/lib/release/lin-x86_64-gcc/libdrd.a)
target_link_libraries(interface ${catkin_LIBRARIES} ${
    PROJECT_SOURCE_DIR}/lib/release/lin-x86_64-gcc/libdhd.a $
    {PROJECT_SOURCE_DIR}/lib/release/lin-x86_64-gcc/libdrd.a)
target_link_libraries (interface ${CMAKE_THREAD_LIBS_INIT})
target_link_libraries(interface usb-1.0)
```

6. Launch roscore.

```
roscore
```

7. In a new command window, navigate to your catkin workspace.

```
cd ~/catkin_ws
```

8. Launch the ReFlex Takktile using the following command.

```
roslaunch reflex reflex_takktile.launch
```

9. Finally, use rosrun to start the interface, also in a new terminal.

```
rosrun interface interface
```

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