Dipartimento di ingegneria dell'informazione e scienze matematiche

Computer and Automation Engineering

Robotics and Automation

Closed loop approach to human-robot handshake

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Contents

Abstract

The following work is focusing on the Human-Robot hand interaction, specifically in the grasping force of the handshake. The handshake event between human beings is a well known task, it can to enable a communication between participants as a mixture of physical features like: grip force of the hand, velocity approach, duration of the handshake, oscillation frequency and amplitude of the arm. The hypothesis is is that in human hand-shaking force control there is a balance between an intrinsic (open–loop) and extrinsic (closed–loop) contribution. The target of this work is to set up an environment in order to test the hypothesis for the human-robot handshake grip force. The environment is built using Robotic Operating System (ROS), which is managing messages among: a Pisa/IIT SoftHand and three FSR 400 sensors managed by an Arduino Uno. A detailed force analysis is needed in order to evaluate the grasping force in the human-robot handshake. The method is presented in 2.2.1 is providing an estimation for the force the human applies on the robot F_h and in 4 is presented a method for estimating the force the robot excerts on the human F_r. The hypothesis is to model the human response to the robot grasp as a dynamical system. A sensorimotor delay is mimicking the reaction time of Central Nervous System (CNS), and varying the contribution of intrinsic and extrinsic force control modify the perceived handshake quality in the user study.

Introduction

Developing a robot capable of performing a smooth human-like handshake is becoming a highly interested topic in the scientific literature. A natural handshake between two humans is a very complex task to replicate, this work just focuses on the interaction force between a robot hand and a human hand. In many parts of the world, the handshake is an important interaction task both for business and social context [1], and an important behaviour to identify is the consensus in the event. It is reasonable to assume that in human-human handshake consensus is reached using not just the haptic sense for the task. Due to the nature of this behaviour it is complex to embed inside a robot, participants will easily distinguish the event with respect to another human or to a robot. It is assumed that humans will naturally take into account for evaluating a handshake not just the grip force but also the skin feedbacks, vision and prior expectations. However, there is little work in the literature studying human-human handshaking, and as such it is not yet possible to describe what constitutes a 'good' or a 'bad' handshake, or even describe a human-human handshake, in a quantitative manner. In Human Robot Interaction [2], the handshake is a really interesting task to focus on, typically leader and follower roles are clearly defined, master action is measured and elaborated to generate reference inputs for the slave controller. In handshake this prior allocation of roles is not defined, it is an inherently bidirectional action in which both sides actively contribute to the task by applying an active and a reactive action at the same time.

Authors in [3] present the design and realisation of a haptic interface performing a robotic handshake, the device is aimed at developing a communication system that allows two people to shake hands while being in different locations.

Another device for the realisation of realistic human-robot handshake is presented in [4], in particular in this work a standard characteristic model of the human-palm compliance is developed, based on human hand anatomy and an empirical study.

The goal of these systems is to appear as a transparent haptic link between the two participants, so that the dynamics of their interaction is similar to in a direct physical handshake. This is different to the goal of this work, which is to realise a robotic autonomous setup able to emulate the human dynamics in handshaking tests. A study in human-robot handshaking [5], investigates the effect on perceived affective properties as the arm stiffness, grasping force and robot facial expressions are changed. A handshake can be considered to include multiple phases. In the approach phase, both partners rely on vision in order to establish contact. Next, in the handshaking phase, each partner exerts a force by closing the hand and receives a force from the other partner. For the case of a human-robot handshake, the robot will receive a force from the human F_h, and also exert a force F_r on the human. Finally, the handshake is concluded by one partner releasing the grasp and the second partner following. A haptic virtual reality system which allows human to make physical handshakes with a virtual partner is presented in [6]. Two approaches are proposed: in the first one robot controller employs an embedded curve and disregards human interaction, in the second one an interactive control is implemented; they verified that the second one is perceived more human-like. In [7] is proposes a Turing-like handshake test to compare a human-human handshake, realised through a haptic interface, with different virtual handshake models. Both [6] and [7] focus on arm trajectory and disregard handshake force. For grasping and manipulation tasks, there is a substantial number of studies looking at how the grip force is modulated [8, 9, 10], these works show that cutaneous feedback is also used to avoid slip. This principle has also been applied to robotic grasping: authors in [11] propose a system for modulating the grasp strength in a reflexive manner to avoid object slippage.

The robot hand chosen for this work (Pisa/IIT SoftHand presented in [12]) had been instrumented with force sensitive resistors in a position where [13] shown important contact pressure distribution. Although force sensitive resistors are really useful in this work thanks to their width, a calibration method is needed in order to obtain an estimation of the human grasping force. Position reference of Pisa/IIT SoftHand can be controlled, but for a more consistent analysis a measure of robot grasping force is needed.

Chapter 1

The Idea

The idea is to create a set of controllers for the human-robot handshake event, using a robot hand developed for research purposes and instrumenting it with three independent FSR sensors which uses an Arduino Uno in order to communicate the data. The FSR sensors are located on the robotic hand so there are no wearing device on the human hand during the execution of the experiments. This choice leads the work to be focused on the theory of the handshake event, and potentially reach robust results with more accurate devices. We are focusing on a general human-robot handshake, knowing that the interaction can vary with participants, f.i. the participant's hand size is affecting the firsts contact points or nominal strength to apply in the handshake can be affected by prior expectations. It is more meaningful then, to study individual differences once the generic case has been studied. The hypothesis is that in human hand-shaking force control, there is a balance between an intrinsic (open–loop) and extrinsic (closed–loop) contribution. It is reasonable to assume that a robot handshake can be evaluated positively by a human if it is as similar as possible to a human handshake, for this reason the presented controllers aim to mirror the behaviour in human-human handshake. the Pisa/IIT SoftHand is a soft under actuated anthropomorphic robot hand, exploiting the idea of synergies [12]. The chosen robotic hand has a single actuated degree of freedom and embeds a dc motor pulling a tendon through in each finger. This physical approach results in a robot hand which can easily adapt to different configurations without modifying the reference position.

Given this hardware set up, some assumption on the dynamics of the event should be done and some notations should be defined. In a handshake between participants A and B, participant A squeezes participant B with a force F_{AB} and is squeezed by participant B with a force F_{BA}. Before contact is made in the handshake, $F_{AB} = F_{BA} = 0$ and other sensory modalities such as vision are relied on. Once contact has been made, the haptic modality becomes dominating (as visual cues of grasping force are minimal). Once cutaneous sensory feedback is available, i.e. after the reaction time of the CNS, the hypothesis is that the interaction becomes closed-loop, so that for participant A the relationship can be expressed as

$$F_{AB} = f(F_{BA}) \tag{1.1}$$

During this phase, it can be assumed that each participant also identifies a nominal handshake strength to apply based on intrinsic factors such as prior expectation (F_{int}). It is known that for grasping and manipulation tasks, humans use feed-forward/predictive controllers to enable reactions faster than the response of the Central Nervous System (CNS) [8, 9].

A closed loop controller on the grasping force seems reasonable, noted as *C1* in 5, this controllers aims to replicate the force perceived from the human F_h. A more complex approach would suggest that intrinsic behaviour are common in human-human handshakes, therefore with the purpose of a human-like robot handshake, other controllers are presented with variations of F_{int}.

Chapter 2

Hardware setup

The hardware must be physically attached in order to reach the goal of a closed loop controller for a handshake. From early approaches as [13], an estimation of the human palm has been used. The sensorized palm is an approximation of the human palm, simple 3D-printed whose shape and dimensions similar to a human hand palm, composed of two shells connected by a load cell. The required approximation consists in assuming that after the first contact point is reached, increasing the reference position is not modifying the shape of the sensorized palm accordingly, human hand palm is modelled as a rigid body. The figure 2 shows the position in which the sensors 1 and 2 are placed according studies in [13].

Figure 2.1: Pisa/IIT SoftHand with FSR sensors for handshake

Histogram from [13] is used as a guide for where to place the sensors, using the notation $F_{fsr,i}$, with $i = 1 \cdots 3$, for the measure of the generic sensor. Sensors $1-3$ in Fig. 2, are used as triggers to identify the contact with the human hand, and 1 and 2 are used for estimating robot force as they were found to be robust towards small variations in the grasp.

2.1 The Pisa/IIT SoftHand

The Pisa/IIT SoftHand is a simple, robust and effective hand designed for grasping and soft manipulation presented in [12]. The hardware is provided with a controller developed by the same group which implements a proportional controller, generically sketched in Fig. 2.3, on the motor position. This enables the researchers to control the Pisa/IIT SoftHand with a reference position.

The proportional coefficient of the controller can be set up as preferred since its

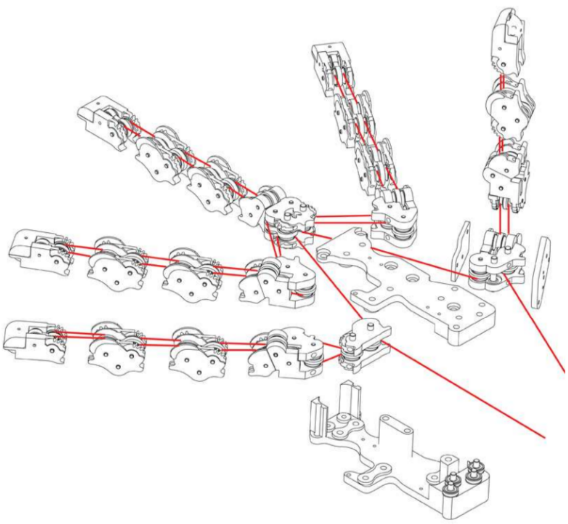

Figure 2.2: Exploited view of the modules of Pisa/IIT SoftHand

encoded in ROS as a *rosparam*, this parameter is thought to range between 0 and 1.0. Setting the parameter to 1.0 is minimizing the error value $e(t)$ between the setpoint $r(t)$ and the output $y(t)$. The successful idea in the design of Pisa/IIT

SoftHand can be found in the flexibility of the joints and the wide range of usage. Having a single motor to control makes the robotic hand really easy to control but introduce uncertainty on the position of each finger. A tendon is running through all the fingers and is pulled by the internal dc motor, therefore a useful available information is the overall tick-position of the Pisa/IIT SoftHand. Constraints on the closure position q are defined as follows:

$$q \in \mathbb{N} : \begin{cases} max(q) = 19000 & \text{(robot hand fully close)} \\ min(q) = 0 & \text{(robot hand fully open)} \end{cases} \tag{2.1}$$

The device has an internal value returning to the system the real tick position q_{output}, this value is compared with the referenced one in the controller q_{ref}. The real tick position is a value that must be calibrated manually using administrative tools provided by the manufacturers. The calibration is manual which means that the robot hand is manipulated to be into a fully open position and the program save that position as the zero tick position.

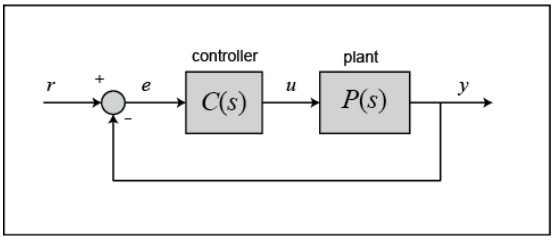

Figure 2.3: Block Diagram Proportional controller in a feedback loop

2.2 The Sensors

The core of a closed loop controller for human-robot handshake is to control the robot force F_r given the human force F_h. FSR sensors are used for measuring the human force but mathematical tools are used to estimate the robot force from its pose.

The Force Sensitive Resistors used are placed on the robot hand in a strategical position for two main reasons:

- the study in [13] shows that the grasping force on the approximation of the human palm, is highly involving the considered hand area.
- the task is to measure the human grasping force F_h, and this position enables a decouple from the robot grasping force F_r.

Figure 2.4: FSR 13mm

The FSR sensors are devices that allow to measure static and/or dynamic forces applied on the sensing area, through the variation of an electric resistance. The main advantage of these devices is the low cost per-unit, little space required for installation (thickness under 1.25mm) and the force sensitivity range up to 100N.
As robust polymer thick film devices, the FSRs, exhibit a decrease in electric resistance with increase in force applied to the surface. By theory is considered that when a force is applied the resistance changes approximately linear in a logarithmic plot [14]. A simple force to voltage conversion is physically implemented as suggested the manifacturer, in fig. 2.5 is shown a snippet of the above cited data sheet. For this work RM is fixed to $3.3k\Omega$.

These mentioned sensors are the more natural choice for handshake experiments since their thickness keeps the size of the robot hand reasonable for the task. Ideally using more sensors allow to get more relevant data but the surface available on the Pisa/IIT SoftHand is limited. The choice in the number of FSR sensors comes from the trade off between using lots of FSR sensors but with a smaller area and using a smaller amount of sensors but with higher area. The first configuration does not ensure the contact among experiments with different participants and the second configuration leads to physical bending of the sensors

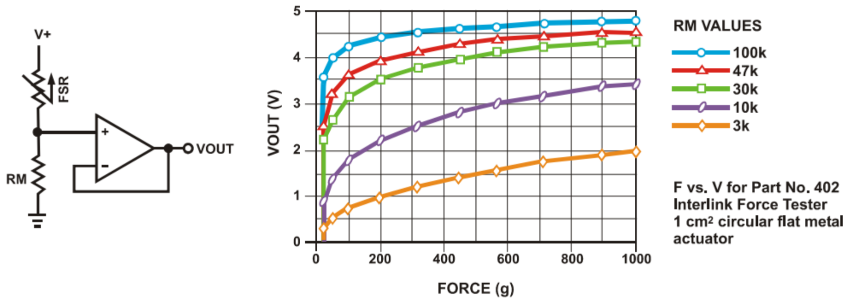

Figure 2.5: FSR Datasheet snippet

and influences the consistency of the readings.

2.2.1 Calibration of FSRs

The calibration procedure of a sensor is a really important task, since it allow to compare experiments and to provide consistent results. The first voltage-to-force relation for the FSRs comes from a manufacturer sketch which is returning force proportionally with standard of gram-force. This first approach is considered not consistent so an ad-hoc calibration experiment is required for estimating the human grasping force. As shown in [15], load cells can be used as 'ground truth' to calibrate force sensitive resistors.Using a *sensorized palm* developed in [13], sketched in Fig. 2.6 which embeds a load cell and placing the FSR sensors accordingly with the position of the sensors 1 and 2 on the Pisa/IIT SoftHand 2; values from FSRs and the load cell are compared.

Mathematical regression tools have been used in order to find a model that explain the values from the sensors compared to the force of the load cell. Although an exact calibration of FSR sensors is not the target of this work, a model has been fitted to the data in the force-range of interest of this work. The configuration for the calibration experiment, with the *sensorized palm* and two FRS sensors is shown in Fig. 2.7. The experiment consists in apply a grasp to the device including not exclusively, the FSR sensors in the grasp. Six calibration experiments were performed, with three different subjects. In each test, the subject was asked to repeatedly grasp and release the sensorized palm, and FSRs and load cell values were recorded. A cubic polynomial is fitted to the data, as shown in Fig. 2.8. This allows to estimate the human grasping force F_h. Although there is some error in the fit, it is observed that for a given handshake grasp between a participant and the robot the estimate of F_h is monotonic and with relatively low variation—the main source of variation comes from the human grasp configuration.

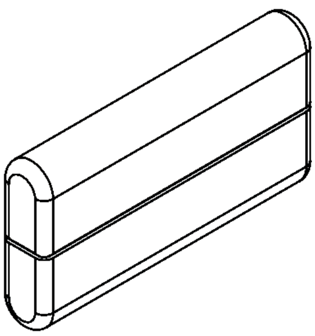

Figure 2.6: Sensorized palm

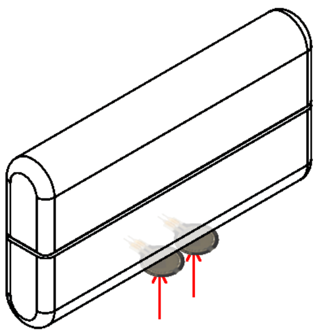

Figure 2.7: Sensorized palm with FSRs

Force is exchanged during a handshake only after the reference position has reach the first contact point q_0, therefore for values of $q < q_0$ no force will be exchanged in the handshake. The *sensorized palm* is used in order to seek the force behaviour of the FSR sensors for values of the reference position $q > q_0$. It can be seen that once the hand makes contact with an object at position $q_a = q_0$, if it can be modelled as a rigid body, the actual hand configuration cannot change. Increasing the reference position result in a relationship that can be approximated as linear, between the difference $q - q_0$ and the force that the hand is applying to the object, F_r, i.e.

$$F_r(q) = \begin{cases} k_r(q - q_0) & \text{for} \quad q - q_0 \geq 0 \\ 0 & \text{for} \quad q - q_0 < 0 \end{cases} \tag{2.2}$$

If the linear coefficient k_r and position q_0 were known, we therefore could use this relationship to estimate F_r from q. Where F_r is the force during the handshake applied by the robot, q is the reference position sent to the device, $q0$ is the first contact point and k_r is a constant parameter to seek.

Note that in handshaking experiments, in which the robot hand interacts with humans' ones, q_0 is a function of the human hand size, so it will change when shaking hands with different partners, furthermore due to human hand compliance, while squeezing the hand, we will have $q_a \neq q_0$ and their difference is proportional to F_R. Assuming to be in a static configuration for $q_a \geq q_0$, the exchanged force is equally distributed in both the human F_h and the robot F_r, i.e.

$$F_R = \begin{cases} k_H(q_a - q_0) = k_R(q - q_a) & q - q_0 \geq 0 \\ 0 & q - q_0 < 0 \end{cases} \tag{2.3}$$

Taking $N = 2$ as the number of FSR sensors installed on the Pisa/IIT Soft-Hand, $F_{fsr,i}$ as the measure of the generic $i - th$ sensor,the human grasping force F_h is estimated as

$$\hat{F}_{fsr} = \sum_{i=1}^{N} F_{fsr,i} \tag{2.4}$$

Using the Matlab Curve Fitting toolbox, we fitted a cubic polynomial to the experimental data and obtained a relationship between the sum of the measure of the sensors $\hat{F}_{fsr}$ and the load cell force F_{fsr}. The relationship can be expressed as:

$$F_{fsr} = 2.86 \cdot 10^{-9} \cdot \hat{F}_{fsr}^{3} - 1.85 \cdot 10^{-5} \cdot \hat{F}_{fsr}^{2} + 0.049 \cdot \hat{F}_{fsr} \tag{2.5}$$

Forcing the equation to include the origin is a natural choice to avoid an offset in the force estimation f.i. if the measure of the FSRs is close to zero then the value of F_{fsr} must be close to zero. The variable F_{fsr} is estimated from the load cell, and is assumed to be equal to the human grasping force F_h.

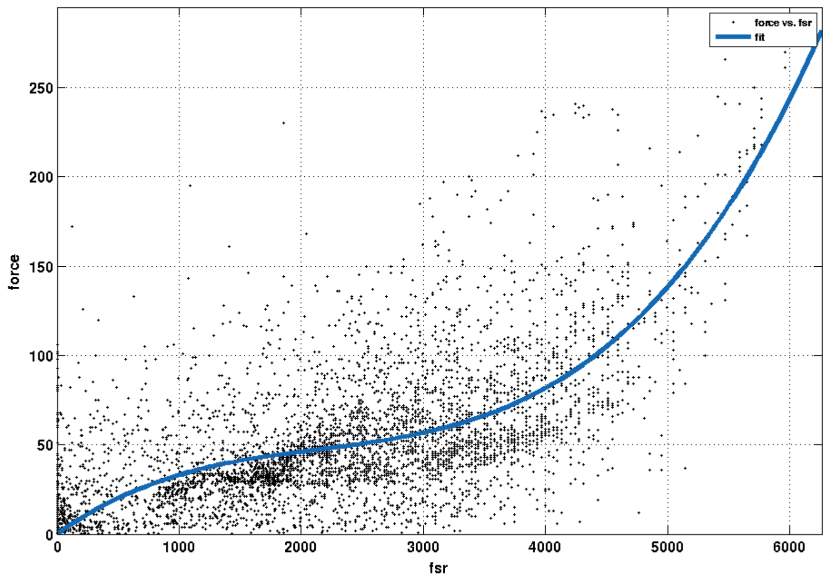

Figure 2.8: FSRs vs. Load Cell data

Obviously, more advanced models can be fitted in order to have FSR sensors measurements with a higher precision, but for the specific task required in this work is considered sufficient the fitted equation in (2.5). The handshake event is involving grasping forces in a limited range of forces, the fitted equation exists for $\hat{F}_{fsr} \in \mathbb{R}$ but, physical limitation of the hardware (max absorbed current) are ensuring the upper bound of the force. Till this point nothing has been done on the Pisa/IIT SoftHand, the available information is that FSR sensors are returning an estimation of the human grasping force F_h and have been calibrated according to a load cell sensor, therefore forces in the following chapters will be intended to be Newton scaled.

Chapter 3

Software setup

The described experiments can be implemented using a software capable of exchanging informations between robots, without the interaction of a human. A tool named Robot Operative System has been chosen in order to manage the informations between the devices involved in these experiments.

3.1 Ros

The Robot Operative System (ROS) is a set of frameworks and libraries useful for robot software development. The logic of this software is really intuitive, it lets the developers to represent a device as node inside a graph. The most important node is this graph is the *Master*, which is managing all the messages in the system. Each node in order to send/receive messages to/from other nodes must communicate his intention to the *Master* node, which is processing the request and forwarding the right informations.
The result is a graph, built as a network of ROS nodes. The main concepts in the ROS graph are ROS Nodes, Master, Parameter server, Messages, Topics, Services, and Bags. Each message in ROS is transported using named buses called topics. When a node sends a message through a topic, then it can be asserted

that the node is publishing a message on topic. When a node receives a message through a topic, then we can say that the node is subscribing to a topic but the production of information and consumption of it are decoupled. Each topic has a unique name, and any node can access this topic and communicate with it, as long as they have the right message type. The type of a message can be chosen among the standard primitive types (integer, floating point, Boolean, and so on) or custom message types can be defined. Custom field structures of messages are useful in order to send an information which is conceptually explained with more than one standard type (f.i a device instrumented with multiple sensors could be publishing all the available measurements in one single topic).

3.2 Nodes

The main aim of ROS nodes is to build simple processes, this makes debug easier and simplify the structure of a project. Each ROS node is written using ROS client libraries such as roscpp and rospy.

3.2.1 Pisa/IIT SoftHand node

Pisa/ITT SoftHand is provided with a variety of ROS packages, in particular, ROS node *qb_force_interface* is the node managing the proportional controller on the position of the Pisa/IIT SoftHand. This node is publishing a topic named: /qb_class/hand_measurement which embeds a custom field structure named: qb_interface/handPos. This custom type message embeds three float values with the meaning respectively of: sensed current position q_{output}, absorbed current, error between q_{output} and q_{ref}.

3.2.2 FSRs node

The FSRs are connected to a bare PCB, connected to an Arduino board, each FSR sensor is following the circuit diagram in Fig. 2.5; This allows the source code flashed on the controller of the Arduino Uno to: read the voltage difference at FSRs terminals, elaborate the information and publish a topic in the ROS environment. A specific protocol called *rosserial* is used in order to implement a ROS node with Arduino, this protocol simplify the development of a ROS node for the Arduino.

3.2.3 Auxiliary nodes

The hardware related nodes of the project are explained above, but in order to manage the informations and to eventually save files during the execution of the experiments, auxiliary nodes are created. The auxiliary nodes are written in C++ or Python and the choice is strictly related to the compatibility with specific library (f.i. *SMACH* State MACHine is a library used to implement state machines, currently only available in Python). Several auxiliary nodes have been created in order to manage:

1. FSR calibration experiments
2. Saving data during experiments
3. Open loop experiments
4. Closed loop experiments

Again, ROS provides the concept of node which is extremely useful for splitting work in smaller and more manageable units.

Chapter 4

Open Loop Experiments

The open loop experiments aim to verify the hypothesis that the human response to a robot handshake can be modelled as a dynamical system. In these experiments human participants are intended to be a calibration system for the robot grasping force F_r. The hypothesis on participant's grasping force is shown in (2.2), participants are asked to apply the force that they are perceiving during the experiments. This introduces a limitation on the evaluation of the data, in fact the equation is assumed to hold only in quasi-static systems.

$$F_h \approx F_r \tag{4.1}$$

As commented in 2.1 the robot hand can be easily controlled with the reference position q, so open loop experiments aim to seek for the relation between q and F_h. A procedure to filter the transient from the data is applied in order to evaluate the relation q vs. F_h when steady states are reached.

For each participant the first contact position is noted as $q_{0,j}$ with $j = 1 \cdots 8$. Assuming (4.1), then look for a function:

$$q = f(F_H) \tag{4.2}$$

During these experiments each reference position of the Pisa/IIT SoftHand is held for 3 seconds, the frequency rate of is set to 100Hz.
A file standard has been created in order to compare different experiments. The file is a '.csv' file with columns [FSR1, FSR2, FSR3, q_{output}, q_{ref}]. All the plots below are obtained as processing files with the previous structure. Each experiment starts with q_{ref} set to 0 and finish with q_{ref} set to 0.

4.1 Safety

The experiments are in open loop so in order to avoid injuries an emergency function is created, if the participant starts feeling pain the key '**x**' on the keyboard must be pressed. The robot hand will set $q_{ref} = 0$ (fully open) and the whole program will be stopped. In case of emergency event a log file is saved and the last rows can be used to understand the configuration just before the event.
The experiments are done with the Pisa/IIT SoftHand in a horizontal position (palm facing down) Fig. 4.1. In this way the weight of the robot hand will not affect the FSR readings.

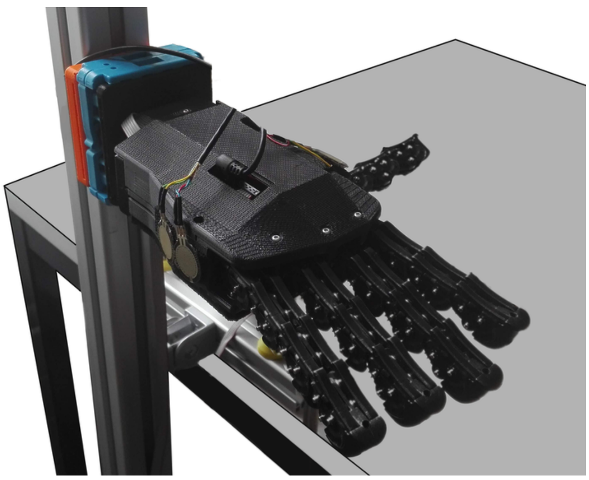

Figure 4.1: Palm facing down environment

Participants

The participants to the experiments have been selected in an heterogeneous fashion from male to female with ages in (24-35 years old). Although the hand sizes available for the experiments are considered sufficient, over bounding the ranges of the previous age set, can provide interesting results. This experimental part is looking for the existing of the relation above mentioned (2.2), therefore it is providing the methodology approach to this problem. Each participant is repeating each experiment five times, this allows to elaborate the outcomes as averages.

4.2 Step input

The simplest signal that can be sent to the Pisa/IIT SoftHand is a step signal on the reference position, in this way the participant's response can be evaluated. The step signal in this experiment is formally a shifted and scaled step signal, the transformation parameters have been chosen in order to start from a position without physical contact to a position where empirical experiments have shown a consistent contact force F_r.

$$Q_r(t) = \begin{cases} q_0 & \text{for} \quad t < t_0 \\ q_1 & \text{for} \quad t \geq t_0 \end{cases} \tag{4.3}$$

4.2.1 Description

The parameters are chosen for the experiment in order to go from a reference position where $F_h \approx 0$ to a reference position where $F_h > 0$ are:

- $q_0 = 8000$
- $q_1 = 15000$
- $t_0 = 3s$

each experiment lasts in total 6 seconds. A correlation between the reference position of the robot hand and the values recorded from the FSRs is expected. Participants are applying a force (F_h) which is assumed to be proportional to the one applied from the robot to their hand during the handshake (4.1). The same experiment has been executed with multiple participants, in order to increase the amount of data available for the model estimation. The values of reference position in this experiment q_0 and q_1, are fixed during multiple trials, therefore the participants are able to predict that at $t = t_0$ a higher reference signal is sent and its amplitude. Although, this behaviour has been considered not consistent to fit, in post processing, a model to the data, it can provide a first relation q vs. F_h in Fig. 4.2.

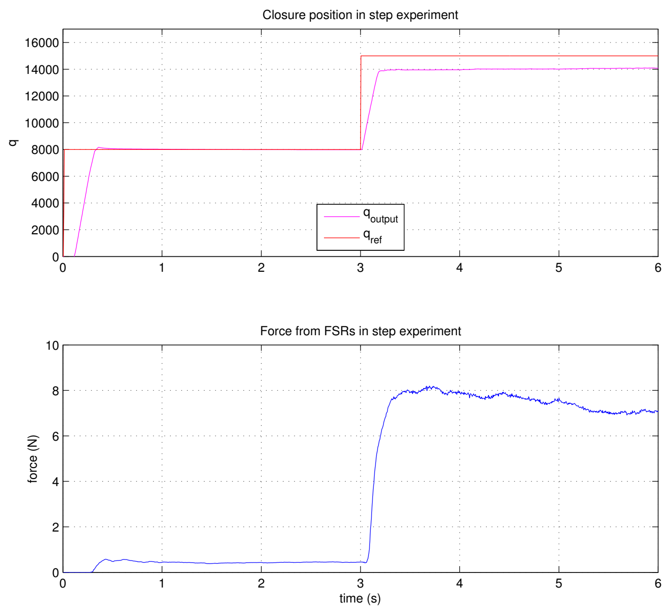

Figure 4.2: Step experiment in time

4.2.2 Transient filter

Giving as input to the system only two different values of reference position, makes more challenging to estimate a realistic model but it can already suggests that a correlation between F_h and q exists. The Fig. 4.2 shows the trend over the time of: q_{ref}, q_{output} and the force F_h; clearly there are parts of these signals which are strictly related to the dynamics of the event. In order to filter these transient behaviours from the data, a time slice has been selected to 1.0 second, which corresponds to $\frac{1}{3}$ of total amount of time of each signal. Removing the information of the time from the previous plots and comparing q against the F_h can highlight the importance of applying a correct transient window, *noted as: TW.*

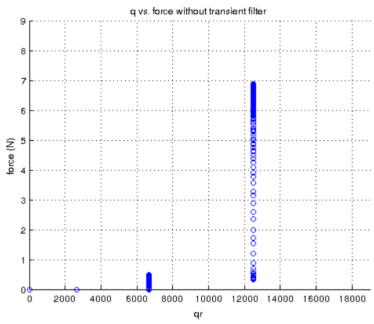

Figure 4.3: TW = 0

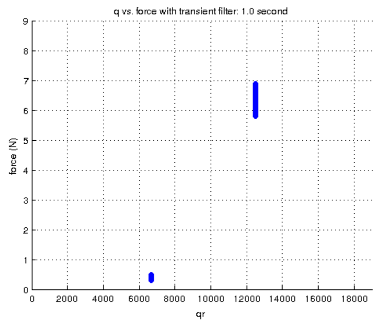

Figure 4.4: TW = 1s

Figure 4.5: q vs. force comparing transient windows

In 4.5 a comparison of the plot of q vs. F_h is shown, a transient window of 1.0 sec. is considered sufficient to reach the steady state grasping force.

4.3 Pseudorandom input

The open loop experiment is trying to identify the relationship between robot closure position q and the robot grasping force F_r. The procedure is to first find the relationship between q and the force that the human apply on the sensors F_h and secondly apply a filter on the transients using the assumption in (4.1) in order to obtain F_r. The step experiment discussed in the previous section is a good starting point for an advanced study. As discussed in 4.1, experiments are repeated multiple times but the previous method allow the participants to understand the behaviour of the robot hand and to predict the step signal amplitude. An approach to solve this issue is to input to the device a random sequence of scaled-step signals, this avoid the participants to forecast the amplitude of the next q_{ref}. A more advanced technique would be to either send a random sequence of scaled-steps and also to randomize the duration of each signal. This last approach can eventually provide more accurate results than the previous one, but the post processing of the data is expected to introduce issues for filtering the transient from each signal.

4.3.1 Description

The Pseudorandom input experiment is an open loop system where a sequence of steps, properly adapted to the range of admissible input closure signals q_{ref} as from (5.1), is set as input to the Pisa/IIT SoftHand while the sensors are acquiring the force F_h. The reason behind a pseudo-randomized sequence is used, can be summarized in two important aspects:

- participants are not able to forecast the next closure position q_{ref} and if each experiment is long enough, the order of each step signal is considered random by each participant,
- during the post processing procedure: having the exact same sequence of q along multiple experiments allow to elaborate the data sequentially.

A single experiment lasts 2'12", and the reference positions sent to the robot hand are randomized with a fixed seed and are unique, this means that if $\hat{q}$ is transmitted for the first time at $\hat{t}$ it is hold for 3 seconds and it won't be transmitted for the rest of the experiment $t > \hat{t}$. Participants response can be

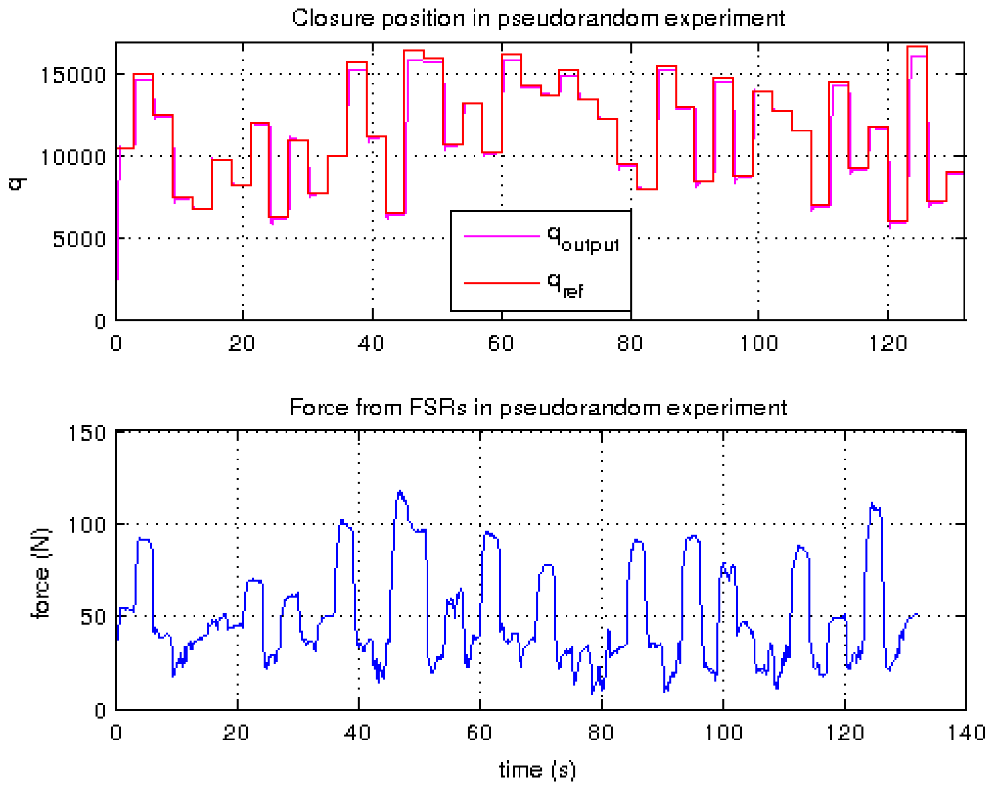

Figure 4.6: Pseudorandom experiment in time

evaluated in Fig. 4.6, where the force F_h during the experiment is plotted, In this phase it is defined an average behaviour for the force exchanged during a human-robot handshake. More formally: in the average model is assumed that the force F_h is hand size independent and is expressed as:

$$F_H = \frac{1}{8}\sum_{j=1}^{8} F_{H,j} \tag{4.4}$$

missing description on shifted $q_{0,j}$ vs q_{ref} for estimating F_r

4.3.2 Transient filter

As for the one step experiment, a technique to filter the behaviours due to dynamics is needed; the same procedure described in 4.2.2 is applied and the transient window (TW) is set to 1.0 sec. Comparing the values of F_h and q is beneficial to understanding how the human reacts to a robot handshaking. The hypothesis is that the higher the values of q are, and higher the force the human will apply on the robot hand. Using the Matlab Curve Fitting toolbox, a cubic polynomial is fitted to the experimental data and the obtained relationship in (4.2), can be expressed as:

$$q = 0.02 \cdot F_r^3 - 2.86F_r^2 + 157.2F_r \tag{4.5}$$

The whole calibration procedure can be therefore summarized in two parts: first using the sensorized palm to express F_h as a function of the FSR measurements, and then use the results from the open-loop experiment to estimate a relationship between F_r and q, requiring (4.1) to hold.

4.3.3 Response time delay

By analysing the data from the experiment in 4.3, a delay response of $0.2 - -0.4$s , is observed in almost all the subjects and in most force variations. This agrees well with the human response time to tactile stimuli [16]. A deeper investigation is computed and an experiment is set up in order to seek for a comfortable value of the time delay in the interaction. Five participants were asked to execute a handshake with the robot in the basic closed loop configuration, so where the robot force F_r is following F_h. A graphic user interface is provided to the

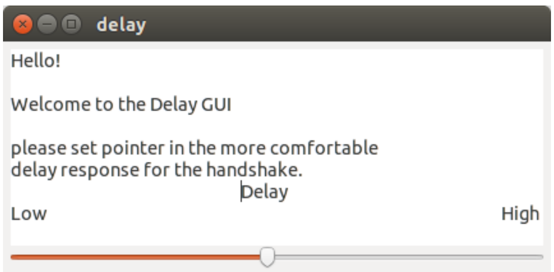

Figure 4.7: GUI for setting delay response time

participants Fig. 4.7, where each of them can vary a slider, controlling the delay response of the sensors. Participants are expected to set the slider in the preferred position, this technically is bypassing ROS topic published by the sensors with a delayed one. At the end of the experiments the preferred time delays are averaged and the mean (120 ms) is considered the most comfortable delay response across all the participants and is applied in all the proposed controllers. insert ros graph showing before the delay node and after the delay node

Chapter 5

Proposed Controllers

All the requirements for building a human-robot handshake interaction are satisfied with the previous chapters. An estimation of F_h is obtained with experiments described in 2.2.1, an estimation of F_r is obtained from 4.3.2 and a measure of the response time delay is set according to 4.3.3. A closed loop control is considered potentially successful for obtaining interesting results in the human-robot handshaking. These controllers can shape the q_{ref} with respect to the F_h with different relations outcomes of experiments described in 4.3.

For all the controllers the human is expected to start and finish the interaction by making contact with the robot hand. Each handshake terminates when no contact is identified. The contact trigger is defined per each FSR sensor when the force is higher than a really small fixed value of force. A binary variable $Contact \in (0,1)$ is defining the contact interaction, it takes value 1 if contact is identified and it takes value 0 for no contact.

$$Contact = \begin{cases} 1 & F_{fsr,i} \geq threshold \quad i \in (1,2,3) \\ 0 & F_{fsr,i} < threshold \quad i \in (1,2,3) \end{cases} \tag{5.1}$$

The value $threshold$ is fixed to $0,1$ N. insert F_H vs F_R plot for C1, C2, C3, C4, C5 for $C_{empirical}$ we don't know how it should be.

5.1 Empirical Proportional controller

A basic approach to a closed loop controller for the task is to assume that: the hand size of each participant is not relevant for the study and the relation between q and F_h is linear. Obviously this method is drastically simplifying the study f.i. the procedure in **??** is not needed since q_0 is not considered. These assumptions are indeed modifying the relation in (2.2) in a more basic one as:

$$q_{ref} = k \cdot F_h \tag{5.2}$$

The reference position of the robot q_{ref} is increasing linearly with the human force. The parameter k is empirically found to span q_{ref} on all its admissible values as explained in (5.1). Although this approach is not consistent, for research purposes (k is empirical), it can provide good information over the assumption that a positive correlation exists between q_{ref} and F_h. The open loop experiments described in 4.3, aim to seek for a consistent relation between these quantities.

5.2 Robot follower (C1)

Assuming a leader/follower interaction, results from open loop experiments 4.3, can be really useful. The instruction given to each participant of the study was to try to apply the same grasping force perceived at each variation of q_{ref}. In these experiments the robot was leading the interaction and participants were following. The interaction roles can now be inverted and the human leads with F_h while the robot follows with F_r. Each participant has a different handsize, therefore q_0 is not constant, this means that the position at which the Pisa/IIT SoftHand realize a contact for the first time changes per j-th participant ($q_{0,j}$). Data acquired during 4.3, are used in order to find a general equation like (2.2), per each participant $q_{0,j}$ is recorded, since it is a function of the hand size. The seek of the equation in the form eq. (4.2), leads to shift the value q_{ref} with $q_{0,j}$ of the j-th participant acquired in that experiment. This approach leads to evaluating the relation between q_{ref} and F_h only after is ensured the contact in all the experiments. It is worth to notice that eq. (4.2) can be generally expressed for $q_{ref} \geq q_{0,j}$.

missing plot

The presented controller has as target the reference force applied by the human on the robot hand, this approach is considering only the extrinsic contribution in the interaction,

$$C1 : F_r = Fh \tag{5.3}$$

A human-human handshake as explained in ch. 1 is supposed to continuously mix extrinsic and intrinsic contributions. It is not plausible that this is a controller implemented by the human: if a robot-robot handshake was performed where both robots implemented this controller then they would never move from the trivial solution of both interaction forces being zero.

5.3 Human follower with low force(C2)

Controller noted as C1 is assuming the human to be the leader in the interaction, but it is worth to test controllers where the robots are leading the grasping force. When participants shake hands with the controller C2, they perceive a constant force F_r not dependent on their force F_h. The robot hand in C2 is leading the interaction. As soon as the human hand is making contact with one of the three FSR sensors, the robot hand applies a constant force F_r, and this force lasts until no contacts are identified. In particular the robot hand is applying:

$$C2 : F_r = 17,4N \tag{5.4}$$

missing plot

5.4 Human follower with high force(C3)

As for C2, controller noted as C3 is behaving as the leader in the handshake interaction. The main difference between C2 and C3 is the nominal strength to apply on the human hand. For this controller the robot is applying:

$$C3 : F_r = 34,2N \tag{5.5}$$

on the human hand. Comparing C2 and C3 can be extremely useful to seek for a consensus behaviour in the participants. If consensus exists in human behaviour, participants will naturally apply higher forces F_r for C3 with respect to C2.

The controller C2 and C3 are assigning a leading role to the robot hand, instead C1 is considering the human as the leader in the interaction. As introduced in ADDREF it is reasonable to assume that in human-human handshakes no roles can be assigned a priori. The next controllers are mixing intrinsic behaviour of C2 and C3 with the extrinsic behaviour of C1. missing plot

5.5 Combined C1 and C2 (C4)

The approach of a controller obtained considering intrinsic and extrinsic contribution, leads to consider C1 and C2 or C3 in the same controller. No assumptions can be done on the relative weight between intrinsic and extrinsic contribution, therefore a homogeneous approach is used and the controller C4 results :

$$C4 = \frac{C1}{2} + \frac{C2}{2} \tag{5.6}$$

The force exchanged during a handshake with the robot hand implementing this controller can be expressed as :

$$F_r = \frac{F_h}{2} + \frac{17,4}{2} \tag{5.7}$$

missing plot

5.6 Combined C1 and C3 (C5)

With C4 a combined controller of C1 and C2 is presented but in order to span different intrinsic contributions C1 is now weighed with behaviour from C3. Controller 5 can be defined as:

$$C5 = \frac{C1}{2} + \frac{C3}{2} \tag{5.8}$$

The force exchanged during a handshake with the robot hand implementing this controller can be expressed as :

$$F_r = \frac{F_h}{2} + \frac{34,2}{2} \tag{5.9}$$

The controllers $C1$, $C2$, $C3$, $C4$ and $C5$ are used in a user study with 15 participants in order to understand how humans perceive differently intrinsic and extrinsic contributions. missing plot

Chapter 6

Results

Conclusion

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