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Computer and Automation Engineering

ROBOTICS AND AUTOMATION

A CLOSED LOOP APPROACH TO HUMAN-ROBOT HANDSHAKE

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Contents

to my father Alfiero Vigni

to my mother Luz Margarita Frias Frias

to my brother Alessandro Vigni

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 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 we want to test in this work, is that in human-human handshake there is a balance between an intrinsic (open loop) and extrinsic (closed loop) contributions. Thus, the force applied by a participant in a handshake results as a trade off between the intrinsic force strength and the force perceived from the partner. The target of this work is to develop an experimental setup in order to test the hypothesis for the human-robot handshake grip force, assuming to shape the robot handshake controller as the closest to the one implemented by humans. A 3D–printed object whose shape and dimension similar to a human hand palm, is used in order to estimate the human grasping force. Relying on the human tactile response, an open loop experiment is run in order to estimate the robot grasping force. A sensorimotor delay is introduced to imitate the reaction time of Central Nervous System (CNS). Five controllers are presented in this work and a user study is run in order to evaluate aspects like: the handshake quality, the human-likeliness of the handshake and the robot personality. The work is born from a collaboration between SIRSLab (Siena) and Disney Research (Zürich) and the results were submitted to RA-L/ICRA 2019 with title: *The Role of Closed-Loop Hand Control in Handshaking Interactions*. The innovative idea is presented as a force controller obtained considering the inner behaviour of the robot, kept as a constant in this work, and the force applied from the human participant. This method allows for the robot hand to: define its own dynamics and modulate the applied force in order to reach an agreement with the human.

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 businesses and social contexts [1], and an important behaviour to identify is the consensus in the event. It is reasonable to assume that in human-human handshake, an agreement in the exchanged force is reached. Due to the nature of this behaviour it is complex to embed inside a robot. It is assumed that humans 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. Therefore, in a human-robot handshake, participants will easily distinguish the event with respect to another human or to a robot. In Human Robot Interaction [2], the handshake is an 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 as sketched in Fig 1.1. Finally, the handshake is concluded by one partner releasing the grasp and the second partner following.

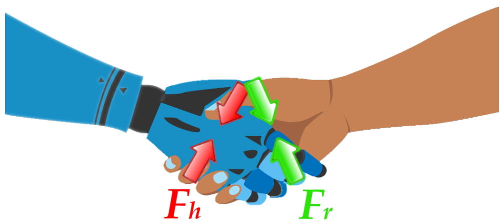

Figure 1: Sketch human-robot handshake

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 proposed 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) is a soft under actuated anthropomorphic robot hand, exploiting the idea of synergies [12], it had been instrumented with Force Sensitive Resistors (FSR) 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 proper method is needed in order to obtain an estimation of the human grasping force F_h. The reference position of Pisa/IIT SoftHand can be controlled and measured, but for a more consistent analysis a measure of robot grasping force F_r is required.

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 devices on the human hand during the execution of the task. Having a single actuated degree of freedom (DOF) in the robot hand, the handshake event can be modelled as a grasping task. This choice leads the work to be focused on the theory of the handshake event, and potentially reaches robust results with more accurate devices. We are focusing on a general human-robot handshake, knowing that the interaction can vary with participants, e.g. 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. 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 chosen robotic hand has a single actuated DOF 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 is the first presented approach, noted as *C1* in chap. 5, it aims to follow the force perceived from the human F_h. This solution runs under the leader/follower logic of Human Robot Interaction with null robot intrinsic contribution. However, due to the specific task required by this work, no roles should be assigned. 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}. More formally, the handshake grip force of participant A is assumed to have the form:

Figure 1.1: Sketch human-robot handshake

$$F_{AB} = f(F_{int}, F_{BA}) \tag{1.2}$$

where F_{int} is the intrinsic contribution of participant A and F_{BA} is the force contribution of the partner.

Chapter 2

Hardware setup

The robot hand and the FSR sensors must be combined in order to reach the goal of a human-like controller for handshaking. The sensorized palm is an approximation of the human palm, simple 3D-printed object whose shape and dimensions similar to a human hand palm, composed of two shells connected by a load cell [13]. Using this approximation implies 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 2.1 shows the position in which the FSRs are placed.

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 on the robot hand, using the notation $F_{fsr,i}$, with $i = 1 \cdots 3$, for the measure of the generic sensor. Sensors $1-3$ in Fig. 2.1, 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. The contact trigger is defined per each FSR sensor when the force is higher than a 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.

$$Contact = \begin{cases} 1 & F_{fsr,i} \geq threshold \quad i \in 1,2,3 \\ 0 & F_{fsr,i} < threshold \quad i \in 1,2,3 \end{cases} \tag{2.1}$$

The value $threshold$ is fixed to $0,1$ N. it is meaningful to study the force exchanged in the interaction only for $Contact = 1$.

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, it is designed to range between 0 and 1.0. Setting the parameter to 1.0 is minimizing the error value $e(t)$ between the setpoint q_{ref} and the output q_{output}. 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 introduces 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 position of the Pisa/IIT SoftHand. Constraints on the closure position q are defined as follows:

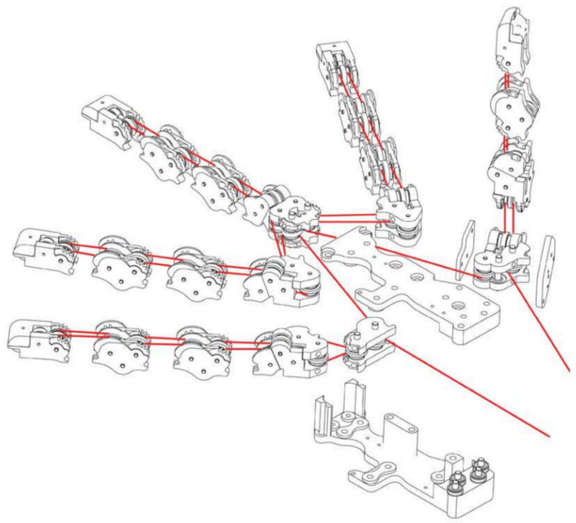

Figure 2.2: Exploited view of the modules of Pisa/IIT SoftHand

$$q \in \mathbb{N} : \begin{cases} max(q) = 19000 & \text{(robot hand fully close)} \\ min(q) = 0 & \text{(robot hand fully open)} \end{cases} \tag{2.2}$$

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. In Fig. 2.3 a block diagram is sketched for the robot hand system, it is ensured by the manufacturer that for $k \in (0, 1]$ the system is marginally stable. The command to the plant *Robot Hand*, for this work is the current absorbed by the DC motor i. However, the models for C and for *Robot Hand* are not provided.

This robot hand is considered interesting for the purpose of this work, but it is provided without any sensor. The task of combining sensors on this hardware is useful both for a closed loop approach and for an open loop approach of the

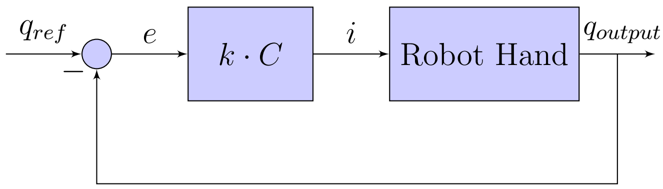

Figure 2.3: Block Diagram Robot Hand System

human-robot handshake. Sensors can be used for either identify the beginning of a handshake ($Contact = 1$) and to provide a measure of the human grasping force F_h. Thanks to the adaptability of this robot hand the handshake task can be approximated with a grasping task. The speed of the robot $\dot{q}$ is bounded, so the input must be considered a saturated ramp rather than a step. If the robot was moving very fast, this could be expected to stimulate other mechanoreceptors in the human and therefore invoke a different response.

2.2 The Sensors

Force sensitive resistors (FSR) 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.

Figure 2.4: FSR 13mm

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].

The FSRs 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.

- this position enables to decouple the human grasping force F_h from the robot grasping force F_r.

This approach is successful for the both required tasks for the sensors:

- provide a measure of human grasping force F_h,
- trigger the *Contact* variable that identify the first contact point.

A simple force to voltage conversion is physically implemented as suggested by the manufacturer, 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

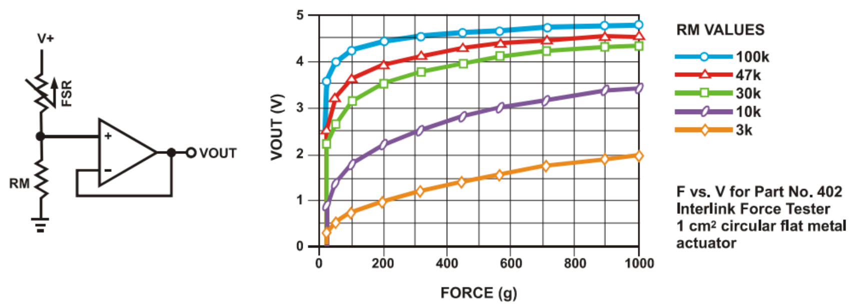

Figure 2.5: FSR Datasheet snippet

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 FSRs comes from the trade off between using lots of FSRs 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 and influences the consistency of the readings.

2.2.1 Estimation of F_h

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 experiment is required for estimating the human grasping force F_h. 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 in Fig. 2.1; values from FSRs and the load cell are compared.

Mathematical regression tools have been used in order to find a model that explains the values from the sensors compared to the force of the load cell. The configuration for the experiment, with the *sensorized palm* and two FSR 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. Force is exchanged during a handshake only after the reference position has

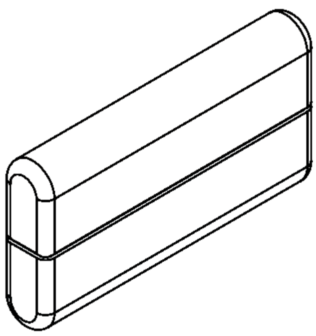

Figure 2.6: Sensorized palm

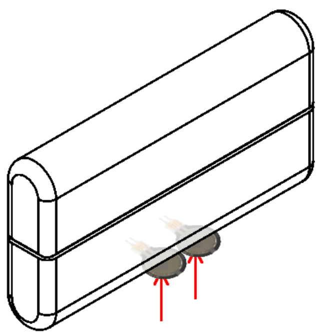

Figure 2.7: Sensorized palm with FSRs

reach the first contact point q_0 ($Contact = 1$), 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 $q > q_0$ ($Contact = 1$). 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.

$$F_r(q) = \begin{cases} k_r(q - q_0) & \text{for} \quad q - q_0 \geq 0 \\ 0 & \text{for} \quad q - q_0 < 0 \end{cases} \tag{2.3}$$

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, q_0 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.

$$F_R = \begin{cases} k_H(q_a - q_0) = k_R(q - q_a) & q - q_0 \geq 0 \\ 0 & q - q_0 < 0 \end{cases} \tag{2.4}$$

The force applied on the robot hand is assumed to be the sum of the FSRs, taking $N = 2$ as the number of FSR sensors on the Pisa/IIT SoftHand, $F_{fsr,i}$ as the measure of the generic $i - th$ sensor,

$$\hat{F}_{fsr} = \sum_{i=1}^{N} F_{fsr,i} \tag{2.5}$$

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:

$$F_{fsr} = 2.86 \cdot 10^{-9} \cdot \hat{F}^3_{fsr} - 1.85 \cdot 10^{-5} \cdot \hat{F}^2_{fsr} + 0.049 \cdot \hat{F}_{fsr} \quad (2.6)$$

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.

$$F_h = F_{fsr}$$

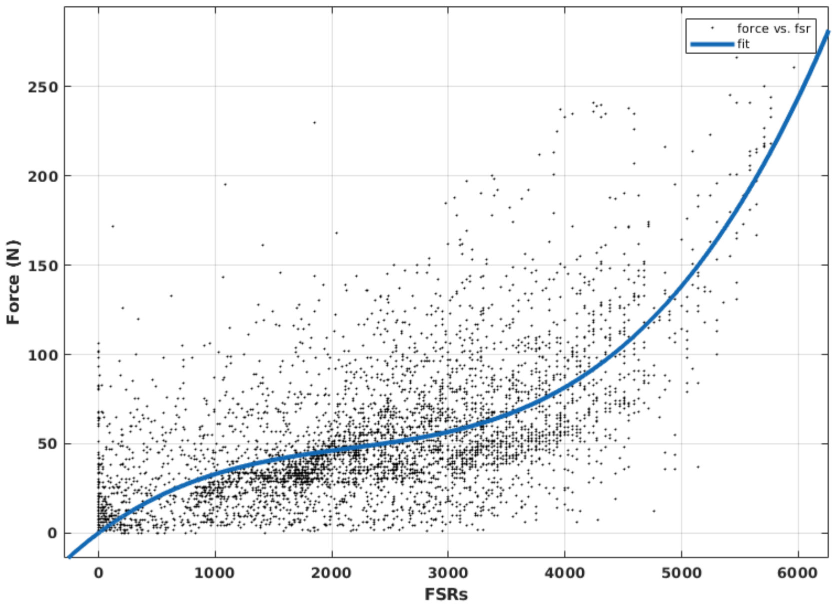

Figure 2.8: FSRs vs. Load Cell data

Obviously, more advanced models can be fitted in order to have FSRs measurements with a higher precision, but for the specific task required in this work is considered sufficient the fitted equation in eq. (2.6). The handshake event is involving grasping forces in a limited range, 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 fitted according to a load cell sensor measurements. F_h is the estimated human grasping force and is expressed in Newtons.

Chapter 3

Software setup

The described experiments are 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 an open-source 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 in 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 *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 pro-

duction 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, etc..) 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 sample 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 FSRs 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 it on a topic.A specific protocol called *rosserial* is used in order to implement a ROS node with Arduino, this protocol simplifies 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 libraries (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:

1. Estimate F_h,
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 eq. (2.3), 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 Sec. 2.1 the robot hand can be easily controlled with the reference position q_{ref}, so open loop experiments aim to seek for the relation between q_{ref} and F_h. A procedure to filter the transient from the data is applied in order to evaluate the relation when steady states are reached.

For each participant the first contact position is noted as $q_{0,j}$ with $j = 1 \cdots 8$. Assuming eq. (4.1) to hold, the function to seek has the form:

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

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 the saved log can be used to understand the configuration just before the emergency event.
The experiments are done with the Pisa/IIT SoftHand in a horizontal position (palm facing down) shown in Fig. 4.1. In this way the weight of the robot hand will not affect the FSRs readings.

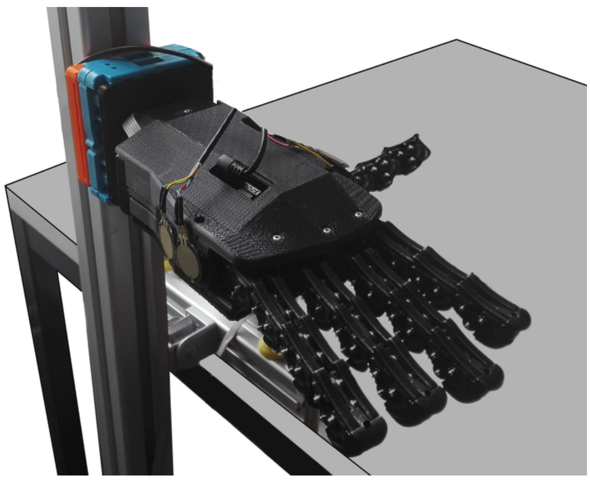

Figure 4.1: Palm facing down environment

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 eq. (2.3), 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_h.

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

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 is set to 3 seconds, so 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 (F_r). 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 an idea of the relation q vs. F_h in Fig. 4.2.

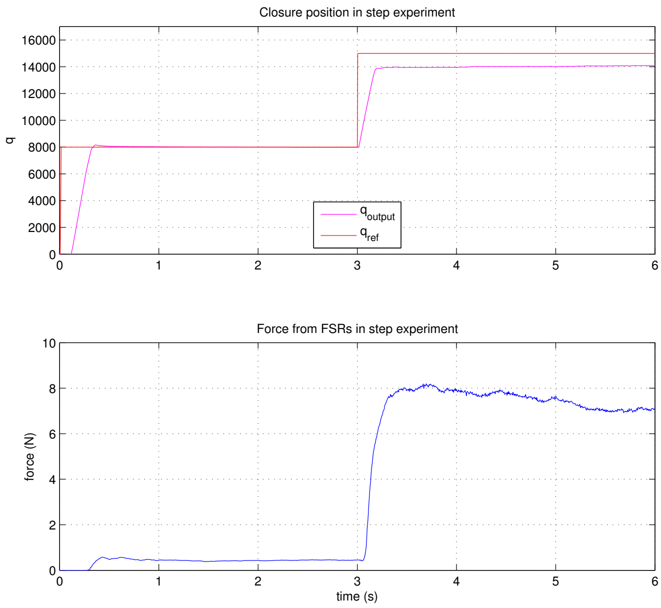

Figure 4.2: Step experiment in time

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_{ref} exists. The Fig. 4.2 shows the trend over the time of: q_{ref}, q_{output} and the force F_h; clearly the human grasping force is affected by the robot position, but there are parts of this signal 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 reference position. Removing the information of the time from the previous plots and comparing q_{ref} against the F_h can highlight the importance of applying a correct transient window, *noted as: TW.*

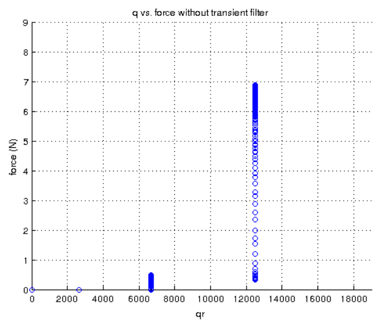

Figure 4.3: TW = 0

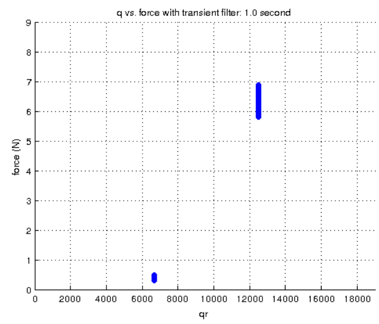

Figure 4.4: TW = 1s

Figure 4.5: q vs. force comparing transient windows

In Fig. 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 in the force interaction.

4.3 Pseudorandom input

The open loop experiment is trying to identify the relationship between robot closure position q_{ref} and the robot grasping force F_r. The procedure is to first find the relationship between q_{ref} and the force that the human apply on the sensors F_h and secondly apply a filter on the transients and using the assumption in eq. (4.1) to obtain F_r. The step experiment discussed in the previous section is a good starting point for an advanced study. As discussed in sec. 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 used one, but the post processing of the data is expected to introduce complexity 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 eq. (2.2), is set as input to the Pisa/IIT SoftHand while the sensors are acquiring the human grasping 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 signal is considered random by each participant,
- during the post processing procedure: having the exact same sequence of q_{ref} 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 $t > \hat{t} + 3$. The sequence of q_{ref} and participants response can be evaluated in Fig. 4.6. In this phase it is defined an average behaviour for the force exchanged during a human-robot handshake. In the average model is assumed that the force F_h is hand size independent and is expressed as:

$$F_h = \frac{1}{8} \sum_{j=1}^{8} F_{h,j} \tag{4.4}$$

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 sec. 4.2.2 is applied and the transient window (TW) is set to 1.0 s. According with the instructions given to

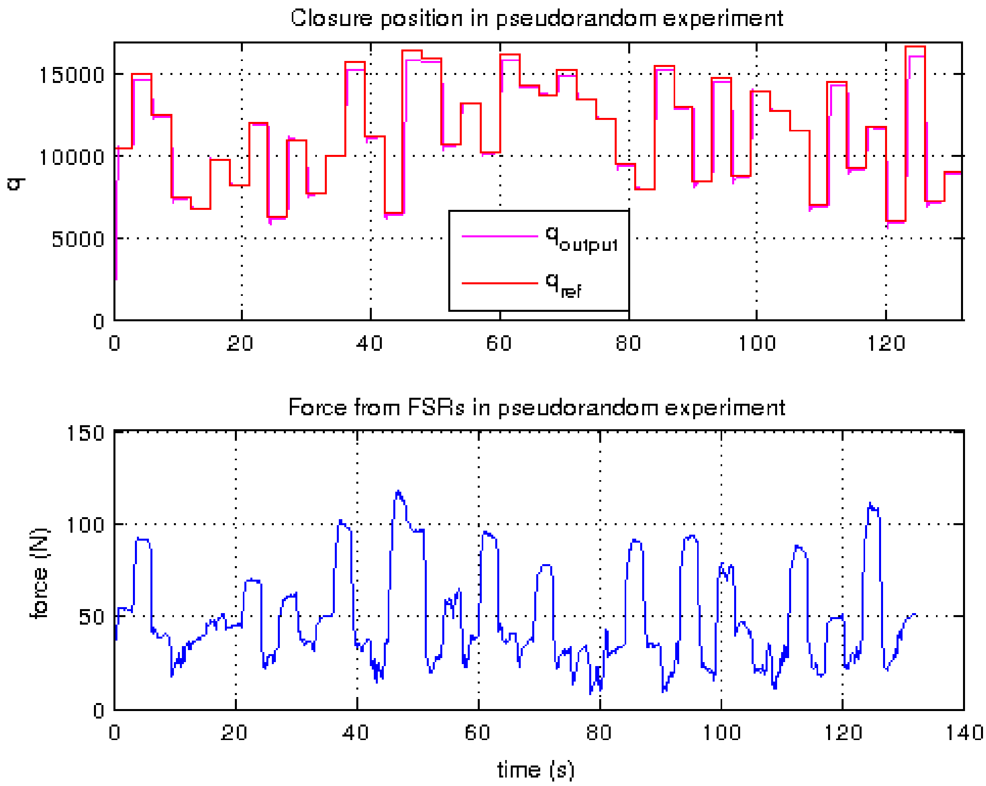

Figure 4.6: Pseudorandom experiment in time

the participants, it is reasonable to assume that after a certain amount of time the human force tends to be a constant per each step. A method to evaluate this behaviour is to measure the standard deviation of the human force with respect to the transient window (TW). The outcome of such evaluation is expected to be a monotonic decreasing function which saturates for high values of TW. The plot in Fig. 4.7 shows the trend of the standard deviation of each of the 44 steps sent to the robot hand. The plot in Fig. 4.8 compress the previous information via a simple average and shows the part of the data considered as transient.

Each force interaction is now considered only after the first second expires, the result is that, in average, the 62.9% of the standard deviation is deleted considering the selected transient window $TW = 1$ s. Comparing the values of F_h and q_{ref} is beneficial to understanding how the human reacts to a robot grasp. The hypothesis is that the higher the values of q_{ref} are, and higher the force the human will apply on the robot hand. Assuming that F_h is hand size independent requires

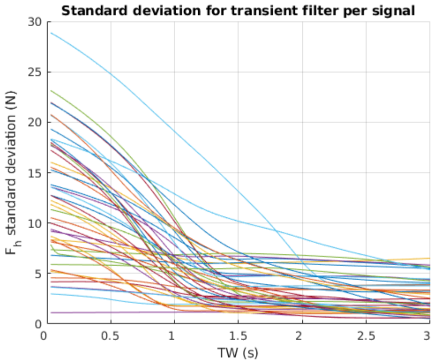

Figure 4.7: std of F_h per 44 steps

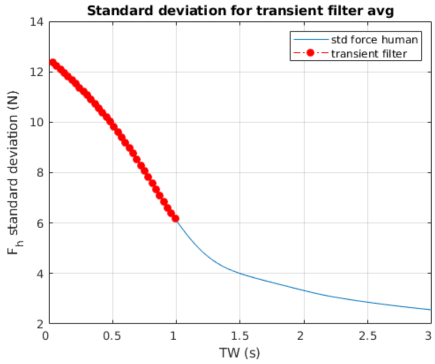

Figure 4.8: std of F_h step averaged

a procedure in order to evaluate correctly the data, that can be summarized as:

- apply transient filter on the data with $TW = 1.0$ s,
- in order to find a general relation between q_{ref} and F_h, data are considered only for values of $q_{ref} \geq q_{0,j}$.

Using the Matlab Curve Fitting toolbox, a cubic polynomial is fitted to the experimental data and the obtained relationship in eq. (4.2), can be expressed as:

$$q_{ref} = 0.02 \cdot F_h^3 - 2.86F_h^2 + 157.2F_h \tag{4.5}$$

The whole procedure can be therefore summarized in two parts: first using the sensorized palm to express F_h as a function of the FSRs measurements, and then use the results from the open-loop experiment to estimate a relation between F_h and q_{ref}. Requiring the quasi-static assumption to hold for eq. (4.5), allow to substitute F_h with F_r and provides a relation between F_r and q_{ref}.

$$q_{ref} = 0.02 \cdot F_r^3 - 2.86F_r^2 + 157.2F_r \tag{4.6}$$

Since the system implemented in the robot hand has as input/output values according to the position, using eq. (4.6) allow to interpret these values q_{output} and q_{ref} with the meaning of forces.

4.3.3 Response time delay

By analysing the data from the experiment in sec. 4.3, a delay response of $0.2-0.4$ seconds, 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 closed loop controller noted in chap. 5 as $C1$, so where the robot force F_r is following F_h.

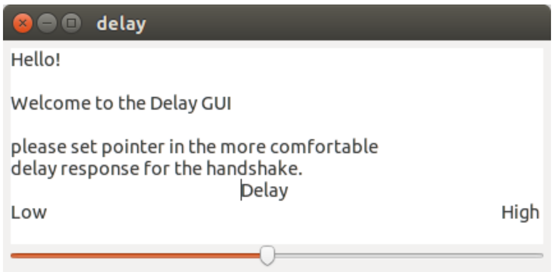

Figure 4.9: GUI for setting delay response time

A graphic user interface is provided to the participants Fig. 4.9, 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. A sketch of the system with and without the delay node is shown in Fig. 4.12.

It is worth to notice that this is not the ROS graph of the configuration, is just an abstract representation of the ROS graph. The node "$C1$" is publishing the reference position q_{ref} to the Robot Hand, which is mapped to robot grasping force using the equation in eq. (4.6).

In Fig. 4.13 a sketch of the ROS graph is shown, nodes are represented as circles, topics are represented as rectangles and the edges are the communications.

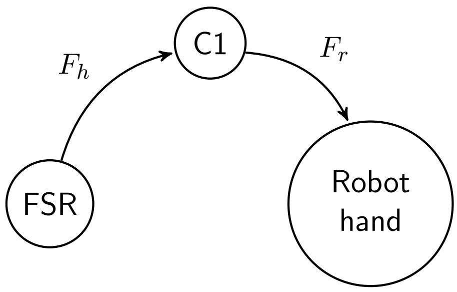

Figure 4.10: Graph without delay node

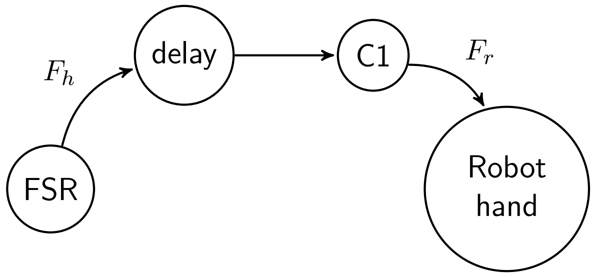

Figure 4.11: Graph with delay node

Figure 4.12: System graph for $C1$ with delay node

A node publishing a topic has an outgoing arrow, a node subscribing to a topic has an incoming arrow. This graph represents the logic for a closed loop controller. The controller $CTRL$ in order to compute the reference position takes as input the human grasping force and the current position of the robot hand. The difference between the current position of the robot hand and the reference position is proportional to the command current as in Fig. 2.3.

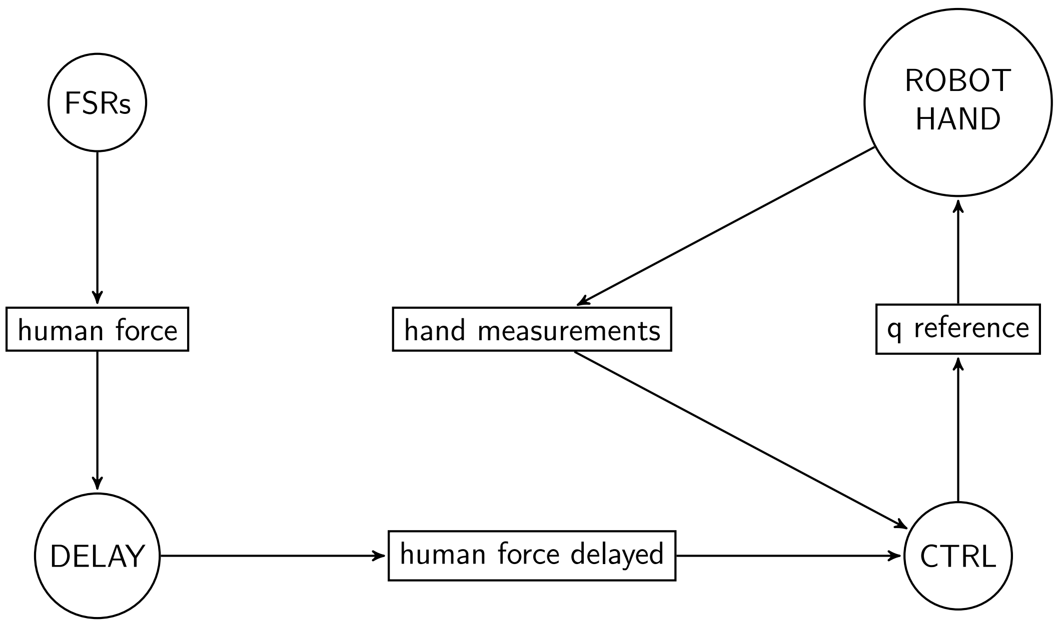

Figure 4.13: sketch of ROS graph

Chapter 5

Proposed Controllers

All the requirements for building a human-robot handshake are satisfied with the previous chapters. An estimation of F_h is obtained from experiments described in sec. 2.2.1, an estimation of F_r is obtained from open loop experiments sec. 4.3.2 and a measure of the response time delay is set according to sec. 4.3.3 to 120 ms. 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 according to the outcome of experiments described in sec. 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 ($Contact = 0$).

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_{ref} and F_h is linear. Obviously this method is drastically simplifying the work f.i. the procedure in sec. 4.3.2 is not needed since q_0 is not considered. These assumptions are indeed modifying the relation in eq. (2.3) in a more basic one as:

$$q_{ref} = k \cdot F_h \tag{5.1}$$

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 eq. (2.2). 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. However, the hand size is an important parameter for this work and in sec. 4.3 it is considered in order to seek for the relation between q_{ref} and F_h.

5.2 Robot follower (C1)

Assuming a leader/follower interaction, results from open loop experiments in sec. 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}. If $q_{ref} \geq q_0$, F_r is increasing with q_{ref} following the eq. (4.6). In these experiments the robot was leading the interaction and participants were following. In the presented controller the interaction roles are inverted and the human leads

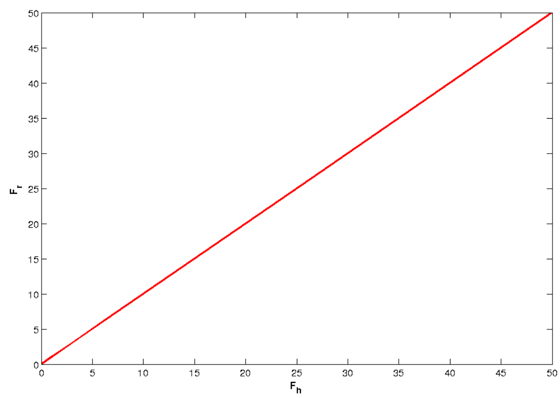

Figure 5.1: Force interaction in C1

with F_h while the robot follows with F_r. Each participant has a different hand size, therefore q_0 is not constant, this means that the position at which the Pisa/IIT SoftHand realizes a contact for the first time changes per j-th participant ($q_{0,j}$). Data acquired during experiment in sec. 4.3, are used in order to find a general equation like eq. (2.3), per each participant $q_{0,j}$ is acquired, 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 evaluates 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

$$q_{ref} \geq \frac{\sum_{j=1}^{8} q_{0,j}}{8}$$

.

The presented controller has as target the reference force applied by the human on the robot hand (F_h) as shown in Fig. 5.1, this approach is considering only the extrinsic contribution in the interaction.

$$C1 : F_r = F_h \tag{5.2}$$

Using the notation in eq. (1.2) for this controller $F_{int} = 0$.

5.2.1 Robot vs. robot

It is considered interesting to evaluate how a controller would perform if implemented in two robotic hands executing a handshake. The above explained controller is following the grip force sensed by the FSRs, without any intrinsic behaviour. Evaluating this event in the contact force interaction area ($Contact = 1$), results in a trivial interaction, both grip forces would never move from zero. Since the target is to seek for the closest approximation of the controller implemented by the humans, it is not plausible that this is the case.

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 a controller where the robot is leading with F_r. 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 using controller $C2$ is leading the interaction and the relation between human and robot grasping force is shown in Fig. 5.2. As soon as the human hand is making contact with one of the three

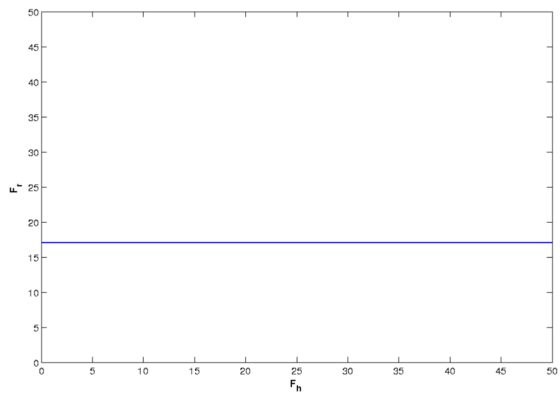

Figure 5.2: Force interaction in C2

FSR sensors ($Contact = 1$), the robot hand applies a constant force F_r, and this force lasts until no contact is identified ($Contact = 0$). In particular the robot hand is applying:

$$C2 : F_r = 17,4N \tag{5.3}$$

The shape of eq. (5.3) is arbitrary and this approach embeds an intrinsic behaviour in a robot hand. Using the notation in eq. (1.2) for this controller $F_{ext} = 0$.

5.3.1 Robot vs. robot

It is interesting to evaluate how this controller would perform if implemented in two robotic hands executing a handshake. The duration of a handshake event can be defined from, [17] which reports a mean handshake duration of 1.0 s. The presented controller does not have any extrinsic contributions, therefore evaluating this event in the contact force interaction area ($Contact = 1$), results in a synchronous interaction where both robots hands reach the same value $F_r = 17,4$ N, and after a 1.0 s. the grips are released and the event is over. In this interaction there is no adaptation in the grip force perceived, therefore it is not considered a good candidate for the human handshake.

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 F_r as shown in Fig. 5.3. For this controller the robot

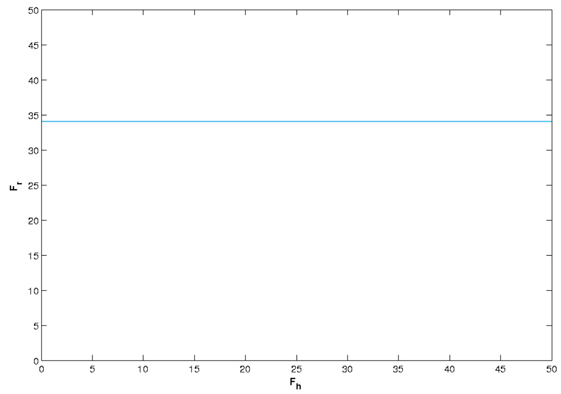

Figure 5.3: Force interaction in C3

is applying:

$$C3 : F_r = 34, 2N \tag{5.4}$$

on the human hand. The value of $34, 2$ N is arbitrary. 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_h for C3 with respect to C2. Using the notation in eq. (1.2) for this controller $F_{ext} = 0$. 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 chap. 1 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.

5.4.1 Robot vs. robot

It is considered interesting to evaluate how this controller would perform if implemented in two robotic hands executing a handshake. The duration of a handshake event is defined as for the previous controller in 1.0 s. The presented controller does not have any extrinsic contributions, therefore evaluating this event in the contact force interaction area ($Contact = 1$), results in a synchronous interaction where both robots hands reach the same value $F_r = 34,2$ N, and after a 1.0 s. the grips are released and the event is over. In this interaction there is no adaptation in the grip force perceived and the FSRs are only used to trigger the handshake event, therefore it is not considered a good candidate for the human handshake.

5.5 Combined C1 and C2 (C4)

The approach of a controller obtained considering intrinsic and extrinsic contributions, leads to consider C1 and C2 or C3 in the same controller. As introduced in chap. 1, the grasping force of each participant of the handshake is assumed to be a function of both intrinsic and extrinsic behaviour. The eq. (1.2) can now be expressed for a handshake between a human and a robot $F_r = f(F_{int}, F_h)$. The intrinsic force of the robot is human independent, for this work is kept as a constant. Since there is no reason to assume that the relative weights of intrinsic and extrinsic behaviour should differ, the proposed solution is:

$$F_r = \frac{1}{2}(F_{int} + F_h) \tag{5.5}$$

This controller is considering the extrinsic contribution of C1 and the intrinsic contribution of C2 where the robot is targeting a constant force during the handshake.

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

In Fig. 5.4 the relation between F_h and F_r is shown.

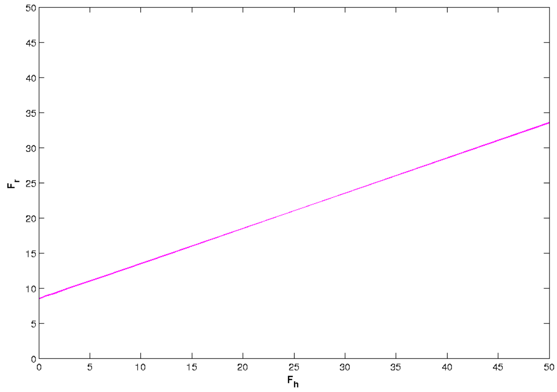

Figure 5.4: Force interaction in C4

The robot grasping force in eq. 5.5 can be expressed as :

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

Using the notation in eq. (1.2) for this controller $F_{ext} > 0$ and $F_{int} > 0$.

5.6 Combined C1 and C3 (C5)

With controller C4 a combination of C1 and C2 is presented but in order to span different intrinsic contributions, C1 is now weighed with the intrinsic behaviour of C3. Using eq. (5.5) it is considered C5 as the simple average of C1 and C3 as:

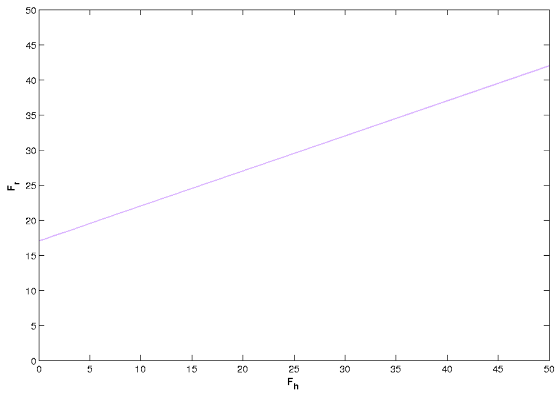

Figure 5.5: Force interaction in C5

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

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

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

Using the notation in eq. (1.2) for this controller $F_{ext} > 0$ and $F_{int} > 0$. 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.

5.7 Robot vs. robot for combined controllers

The proposed controllers aim to replicate the real handshake behaviour of a human. A human-human handshake can be summarized as follows:

- *Approaching.* Before the handshake no force is exchanged and humans relies on vision for starting the interaction ($Contact = 0$).
- *Handshake.* Haptic sensory feedback is dominating, and participants agree to reach a common grip force considering both intrinsic and extrinsic contributions ($Contact = 1$).
- *Termination.* One of the participants release the grasp and the other follows shortly ($Contact = 0$).

It is worth then to study the proposed solutions where the interaction is made by two robot hands running the same logic. Considering the approaching part not relevant for this work and defining a maximum duration of the handshake for terminating the event as presented in [17], an evaluation can be done.

If a robot-robot handshake is performed using in both either C4 or C5, the interaction, from an analytical point of view can provide interesting results. The duration of a handshake event is defined as for the previous controller in 1.0 s. As soon as the binary variable *Contact* takes value 1, both robot hands follows their own law. Denoting the robots by A and B, and their intrinsic forces as F^A_{int} and F^B_{int}, a simple analysis yields that a stable force equilibrium would be reached with:

$$F_A = \frac{2}{3}F^A_{int} + \frac{1}{3}F^B_{int} \tag{5.10}$$

for robot A, and vice versa. Thus, both the intrinsic and extrinsic factors are considered. If the same controller is implemented in robot A and robot B the intrinsic contribution are identical and therefore, the overall interaction result in $F^A = F^B$. This approach can be considered as a first step toward the definition of robot personality, in this work the shape of the intrinsic robot behaviour is a constant but more advanced functions can be used. The equation in (5.10) evaluated for different intrinsic behaviours reveals an agreement in the interaction. Considering the equation for robot B,

$$F_B = \frac{2}{3}F^B_{int} + \frac{1}{3}F^A_{int} \tag{5.11}$$

with the purpose of evaluating the difference between the interaction results in the equation:

$$|F_A - F_B| = \frac{1}{3}|F^A_{int} - F^B_{int}| \tag{5.12}$$

The equation 5.12, provides an evaluation of the agreement force reached at the equilibrium when two robot hands execute the task. The difference between the applied forces F_A and F_B is equal to $\frac{1}{3}$ of the difference between their intrinsic behaviuor as shown in Fig. 5.6.

The higher is the difference in the intrinsic behaviour and the higher is the value toward the agreement, f.i. if $F^A_{int} = 10$ N and $F^B_{int} = 100$ N, at the equilibrium $F^A = 40$ N and $F^B = 70$ N and an agreement is reached. This approach is not affecting the overall stability of the system with intrinsic behaviours kept as constants. Although it is considered interesting to experiment these controllers with non constant shapes of the intrinsic behaviour, no further investigation are

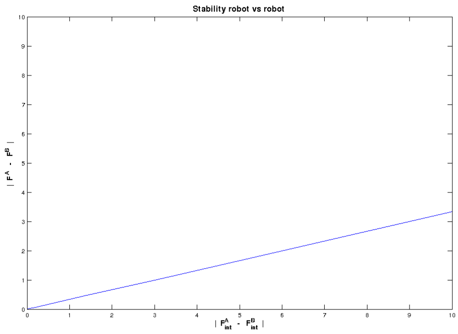

Figure 5.6: Interaction force between two robot depends on their intrinsic behaviuor

done. Further work could focus on this task and compute a stability analysis in order to understand the limits of this approach. F_{int} is intended to model the human prior strength and the behaviour that cannot be evaluated directly from the reading of the human grasping force F_h. If the human-human handshake is a task in which consensus is reached naturally, this method could evaluate prior strength to apply on the handshake.

Chapter 6

User Study results

The controllers C1, C2, C3, C4 and C5 are presented in a user study with 15 participants in order to evaluate the performances and highlight the perceived differences. The five controllers being tested were introduced in the previous chapter and depicted in Fig. 6.1. All controllers were implemented using the sensorimotor delay of 120 ms as described above.

6.1 Experimental procedure

The robot hand was attached to a rigid mount, as depicted in Fig. 6.2. For a more realistic test scenario, we did not impair the vision or hearing of the participants. 15 participants (12 male) were recruited for the study. They received cinema vouchers in return for their participation. The study was approved by the Disney Research IRB. Participants were briefed about the study, and asked to sign a written consent form. As q_0 is dependent on participant hand size, we first carried out a calibration procedure for each participant where we manually closed the robot hand and identified q_0 as the point at which the robot hand would begin to apply a force to the human hand. Participants were then presented with a randomized sequence of the 5 handshaking controllers. Each controller appeared 3 times in the sequence, for a total of 15 trials. For each trial, we asked participants to perform a set of handshakes (not a prescribed number) with the robot hand

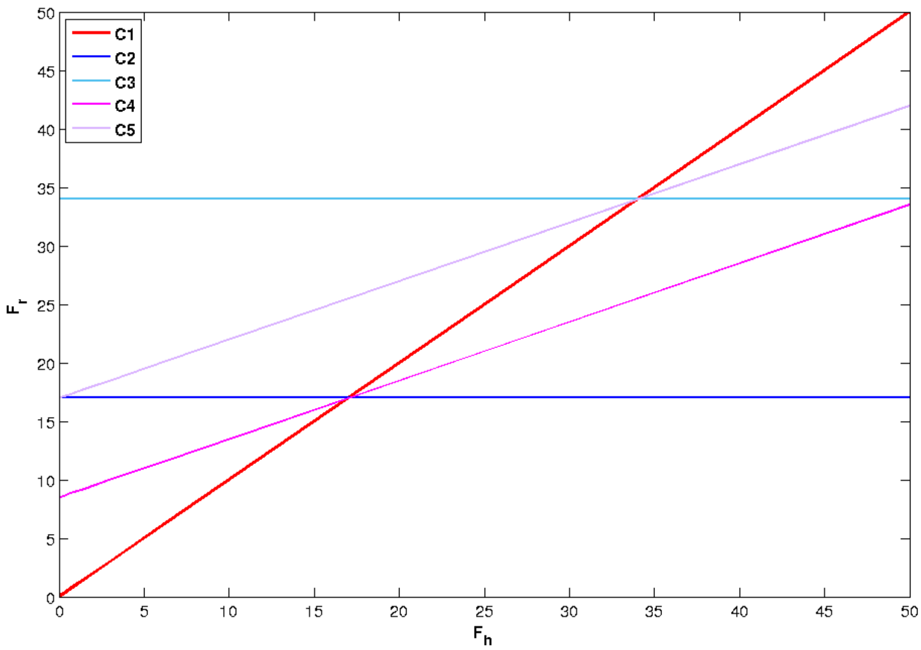

Figure 6.1: Sketch of the behaviour of the 5 proposed handshaking controllers, showing the force exerted (F_r) as a function of the force received (F_h). C1 (robot follower): the robot follows the human, so $F_r = F_h$. C2 and C3 (robot open loop): the robot squeezes with a force which is independent of F_h. C4 (combined controller): the robot squeezes with a force dependent both on F_h (as in C1) and on the robot's intrinsically preferred force (as in C2). Again, C4 has a lower intrinsically preferred force, and C5 has a higher value.

Table 6.1: Likert-scale questions.

	Question	**Scale (1 to 7)**
Q1	Please rate the quality of the handshake	*very poor* to *very good*
Q2	Please rate the human-likeness of the handshake	*very robot-like* to *very human-like*
Q3	Please rate the responsiveness of the robot	*not responsive at all* to *very responsive*
Q4	Who was the leader of the handshaking interaction	*I was the leader* to *the robot was the leader*
Q5	How would you judge the personality of the robot	*shy, hesitant, introvert* to *confident, secure, extrovert*

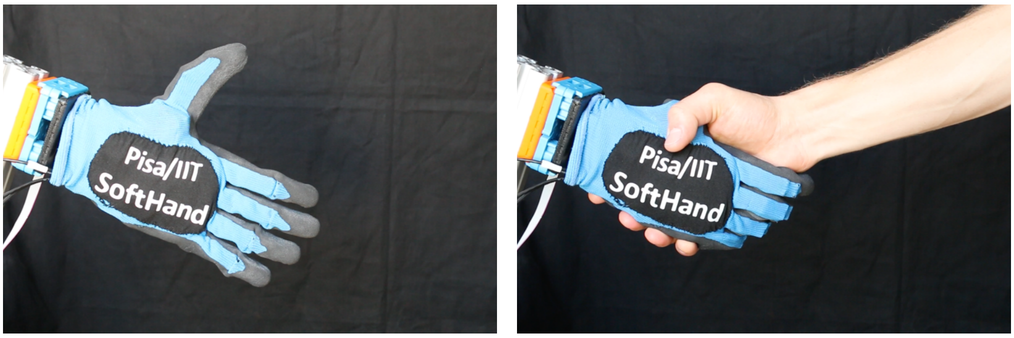

Figure 6.2: Experimental setup for user study, with the robot hand attached to a fixed mount.

and then answer 5 questions as listed in Tab. 6.1. Responses were made on a 7-point Likert scale. The first 3 questions relate to the handshake quality and human likeness, and the last 2 questions relate to perceived personality traits of the robot.

6.1.1 Handshake statistics

Across all handshakes, we can compute some statistics. In total, participants performed 1812 handshakes (on average 8 per trial), with a mean duration of 2.2 s and with a mean value of F_h of 24.8 N. This is longer than would be expected for a human-human handshake, suggesting that participants might be spending longer time in order to better understand robot behaviour. For the open-loop controllers (C2 and C3), F_r is independent of F_h. To determine if the human followed the robot in this controller, we computed the mean value of F_h across all participants for the two conditions C2 and C3. A t-test showed a significant difference between F_h in C2 ($M = 19$, $SD = 10.4$) and C3 ($M = 27.4$, $SD = 19.9$) with $p = 0.0138$. This shows that humans do indeed incorporate closed-loop control for handshaking, and follow the behaviour of the robot.

6.1.2 How are different controllers rated

To analyse the responses from the user study, we first computed for each participant their mean responses for each controller. For each question, we then

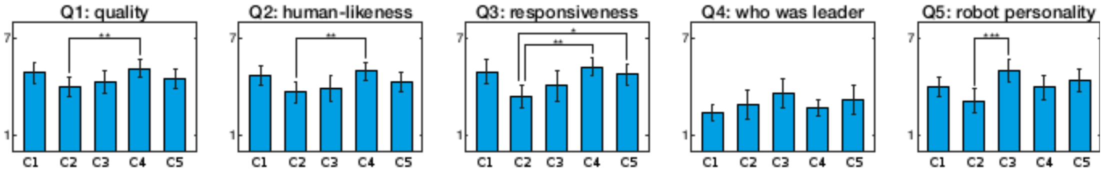

Figure 6.3: Bar charts showing results from user study. Error bars show 95 % confidence intervals. Significant differences between controllers have been indicated with $*$ for $p < 0.05$, $**$ for $p < 0.01$ and $***$ for $p < 0.001$.

performed pairwise t-tests with Bonferroni correction between all pairs of controllers. The results are summarized in Fig. 6.3.

For Q1 (handshake quality) we found a significant difference between controllers C2 ($M = 3.98$, $SD = 1.27$) and C4 ($M = 5.11$, $SD = 1.09$) with $p = 0.0012$. It can thus be seen that there is a perceived improvement in handshake quality between the weaker force open-loop controller and the weaker combined controller.

For Q2 (human likeness) we also found a significant difference between controllers C2 ($M = 3.62$, $SD = 1.39$) and C4 ($M = 4.93$, $SD = 1.27$) with $p = 0.0045$. The same trend as for Q1 is thus seen, with the weaker combined controller being perceived as more human-like than the weaker open-loop controller. In general, from Fig. 6.3, it appears that there is correlation between Q1 and Q2, as would be expected.

For Q3 (responsiveness) we found significant differences between C2 ($M = 3.36$, $SD = 1.54$) and C4 ($M = 5.18$, $SD = 1.32$) with $p = 0.0022$, and between C2 and C5 ($M = 4.76$, $SD = 1.55$) with $p = 0.0370$. The perceived responsiveness of the combined controller, both with stronger and weaker force, is therefore significantly greater than that of the weak open-loop controller. It can be seen that the two open-loop controllers are rated as less responsive than the 3 closed-loop controllers, as would be expected, however for the remaining pairs this difference is not statistically significant.

For Q4 (leader/follower) we did not find any significant effects. In general, responses are towards the lower end of the scale meaning that participants felt that they were the leader in the handshake. We note that although there was no significant difference in leader/follower for C2 and C3, there was still a significant difference in F_h between the two conditions meaning that humans did indeed follow the robot.

For Q5 (robot personality), we found a significant difference between C2 ($M = 3.09$, $SD = 1.58$) and C3 ($M = 4.98$, $SD = 1.67$), with $p = 0.00049$. For the two open-loop controllers, increasing the handshaking force therefore has the effect of making the robot be perceived as more *confident, secure and extrovert* while decreasing the force causes it to be perceived as more *shy, hesitant and introvert*. To a lesser extent, the same effect can be observed in C5, but in this case it is not significant.

Conclusion

The importance of Human Robot Interaction is rapidly increasing in the robotic system field, allowing to achieve long-term applicability of robots in various social domains. This work wants to highlight the Human Robot Interaction of the handshake by proposing five different controllers with various contribution of intrinsic and extrinsic behaviour. The results from the user study are promising and suggests further research toward the idea of a robot independent behaviour in the interaction. The method for estimating the human grasping force from a load cell is considered robust toward variation in the grasp but the great novelty can be found in the method for estimating the robot grasping force presented in chap. 4. An experiment is run and participants are instructed to mirror the perceived grasping force applied by the robot. The open loop system input is a fixed sequence of randomized reference positions. This experiments show the relation between q_{ref} and F_h, under the assumption of a quasi-static interaction, a filter is used to remove the dynamics in the human response. F_h in the above mentioned relation can be substituted by F_r, providing a map from the robot reference position to the robot grasping force. A single expression is assumed to explain the force interaction for values of $q_{ref} \geq q_0$. Although a handshake is a task with high variability with participants, this work has as target to identify a general expression for the task. From the user study in chap. 6 it is worth to notice the significant difference between C2 and C4 in the questions to rate the quality of the handshake and the human-likeliness. With respect to the human follower controller (C2), the result is that:

- participants evaluate better the quality of the controller in which intrinsic and extrinsic behaviour are considered (C4),

- participants evaluate better the human-likeliness of the controller in which intrinsic and extrinsic behaviour are considered (C4).

Although the intrinsic behaviour in C4 and C5 are arbitrary, this results suggest that further research could lead to a deeper understanding of the human-robot handshake event.

Future work

The controllers for human-robot handshake presented in this work are considered a first step towards the idea of having robots merged in the human social contexts. Future works could experiment different anthropomorphic robot hands, and vary the sensors set up. Moreover, this work could help scientists to understand better the human-human handshake. Due to the nature of the human hand and of the handshake task, it is not easy to develop a device (f.i. wearable) in order to study the interaction. This work provides an approach to study human-human handshakes from a general point of view. The robot follower controller can be used to implement a transparent haptic interface for remote human-human handshake. The described sensorized robot hand, could extend its usage for tele handshaking of humans from different locations. The robot follower controller could be implemented in a 1–to–more experiment. f.i. the candidate of a thesis defence could shake hands with all the committee with just one execution of the task. It would be interesting to evaluate how the consensus should be defined in a 1–to–more handshake task. Assuming that humans adapt the strength of the handshake to the one of the partner, the combined method intrinsic/extrinsic could be used for evaluating humans intrinsic behaviour.

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