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Closed loop approach to human-robot handshake

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Contents

1	The state of the Art	2
1.1	The Idea	3
2	Hardware setup	4
2.1	The Pisa/IIT SoftHand	5
2.2	The Sensors	6
2.2.1	Calibration of FSRs	8
3	Software setup	11
3.1	Ros	11
3.2	Nodes	12
3.2.1	Pisa/IIT SoftHand node	12
3.2.2	FSRs node	13
3.2.3	Auxiliary nodes	13
4	Open Loop Experiments	14
4.1	Step input	17
4.1.1	Description	17
4.1.2	Transient filter	18
4.2	Pseudorandom input	19
4.2.1	Description	19

CONTENTS	3
5 Closed Loop controllers	22
5.1 Empirical Proportional controller	22
5.2 Human-calibrated controller	22
6 Results	23

Abstract

The following work is focusing in the Human-Robot interaction, specifically in the dynamics of a handshake. The handshake event between human beings is a well known task, it is able to transmit participants feelings as a mixture of physical features like: strength of the handshake, velocity approach, duration of the handshake, oscillation frequency and amplitude of the arm. The target of this work is to set up an environment in order to test different closed loop controllers for the handshake event. The environment is built using Robotic Operating System (ROS), which is managing messages among: a Pisa/IIT SoftHand, four FSR 400 sensors managed by an Arduino Uno and the auxiliary nodes. The work is splitted in two main experimental parts: calibration and tests. The calibration part is built as an open loop system in which we're interested in understanding the participants grasping force with respect to Pisa/IIT SoftHand's force. The hypothesis is to model the human response to the robot grasp as a dynamical system. Different dynamical models can explain the data retrieved and are tested with closed loop controllers.

Introduction

The handshake event, commonly used, is a natural human interaction and is extensively used worldwide in events like: greetings, introduction routine between human beings and agreements. The scientific approach to handshake between a human and a robot, therefore, must intrinsically deal with low levels human interactions and some assumption must be done in order to focus on the task. The handshake event can be divided in two parts: the approaching and the handshaking. This work is focused on the haptic sense involved during the handshake, knowing that the approaching is mainly executed using non haptic senses(f.i. vision).

A parameter involved in the handshake is the consensus; it allow the human to evaluate a handshake mixing aspects like: duration of the event, dynamics, force exchanged. An important part of this work is to test different controllers with the purpose of evaluating the consensus using closed loop controllers.

Chapter 1

The state of the Art

Develop a robot capable of performing a smooth human-like handshake is still 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 an artificial hand and a human hand. The consensus is a complex task to encode inside a robot, participants will easily distinguish the event with respect to another human or to a robot. A human will take into consideration the skin feedbacks like: the temperature, the humidity and the softness. These are some characteristics that are still not embedded into the hardware available in the market. The aspect taken in consideration in this work is the grasping force exchanged in the handshake. Robots, nowadays, are highly involved in industries where mostly they have to execute repetitive tasks. These kind of robots, when have to grasp objects, commonly uses multi purposes grippers [2], therefore, an accurate choice has been done on the hardware to use in this work.

[7] [8] [6]

1.1 The Idea

The idea is to create a closed loop controller for the human-robot handshake event, using Pisa/IIT SoftHand produced for research purposes at Università degli studi di Pisa and Istituto Italiano di Tecnologia (IIT) and upgrading it with four 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 theoretical part of the handshake event, and potentially reach robust results. 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 chosen robotic hand (Pisa/IIT SoftHand) has 19 degrees of freedom and its main characteristic a single dc motor that is pulling a tendon which is embedded in each finger. This physical approach results in an under actuated robotic hand which can be controlled only by the dc motor and can easily adapt to different configurations without modifying the reference position.

Chapter 2

Hardware setup

The hardware must be physically merged in order to reach the goal of a closed loop controller for a handshake. From early approaches as [5], an estimation of the human palm has been used. The *sensorized palm* idea was to approximate the human palm which is the part of the hand mostly interested during a handshake. The figure 2 shows the position in which the sensors are placed, both sensors n. 1, 2, 3 are placed according studies in [5].

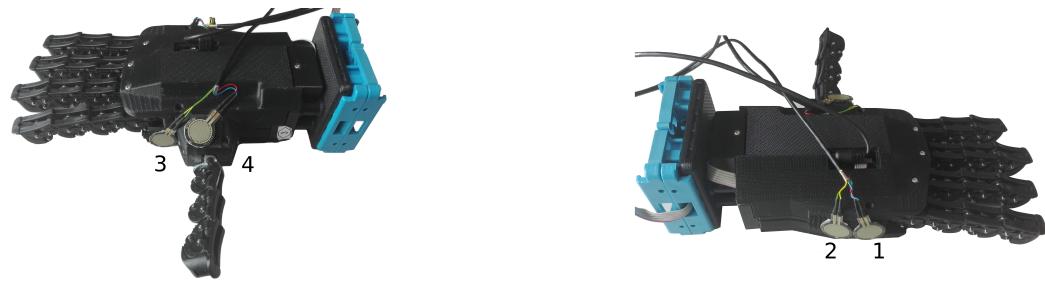


Figure 2.1: Pisa/IIT SoftHand with FSR sensors for handshake

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 [1]. A tick range is provided with the device in order to set a range of possible closure positions, more formally, let's define $q \in \mathbb{N}$ as the closure position of the hand such that $\max(q) = 19000$ (Pisa/IIT SoftHand fully closed) and $\min(q) = 0$ (Pisa/IIT SoftHand fully opened). The hardware is provided with a controller developed by the same group which implements a proportional controller Fig. 2.3 on the motor position. This enables the researchers to control the Pisa/IIT SoftHand with a reference position, without dealing with the current control of the motor.

The proportional coefficient can be set up as preferred since its encoded in ROS

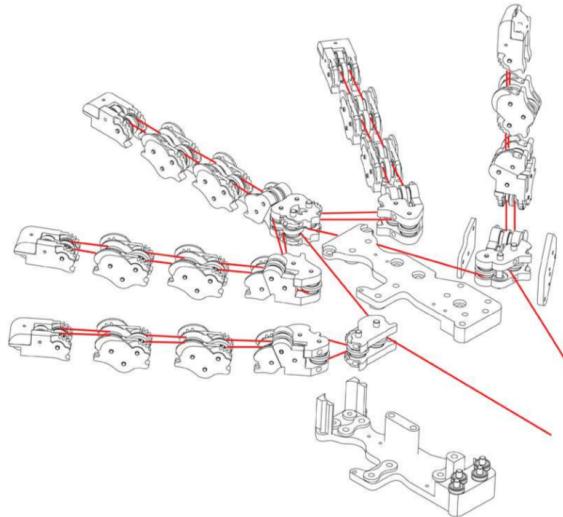


Figure 2.2: Exploited view of the modules of Pisa/IIT SoftHand

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. The reference position $r(t)$ has no 1:1 correspondence with the single physical position of each

finger. 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:

$$q \in \mathbb{N} : \begin{cases} \max(q) = 19000 \\ \min(q) = 0 \end{cases} \quad (2.1)$$

The device has an internal value returning to the system the real tick position, this value is compared with the referenced one in the controller. 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 Pisa/IIT SoftHand is manipulated to be into a fully open position and the program save that position as the zero tick position.

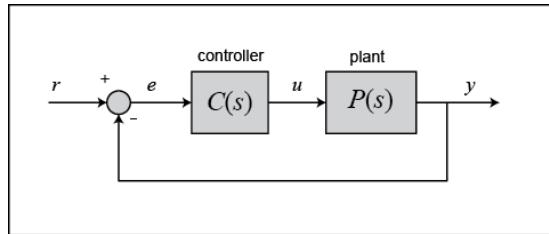


Figure 2.3: Block Diagram Proportional controller in a feedback loop

2.2 The Sensors

The core of the closed loop control is to have a feedback in the whole system which is proportional to the force applied during the handshake from the human.

The sensors used in this work are Force Sensitive Resistors Fig. 2.4 measuring the force applied from the human to the Pisa/IIT SoftHand, in order to decouple this force from the one applied from the Pisa/IIT SoftHand to the human hand,

[5] has been used and the physical position of the FSRs has been setted up accordingly. FSR sensors are devices that allow to measure static and/or dynamic forces applied on the sensing area, through the variation of its 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 20N.

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 [4]. A simple force to voltage conversion is physically implemented as suggested 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 experi-

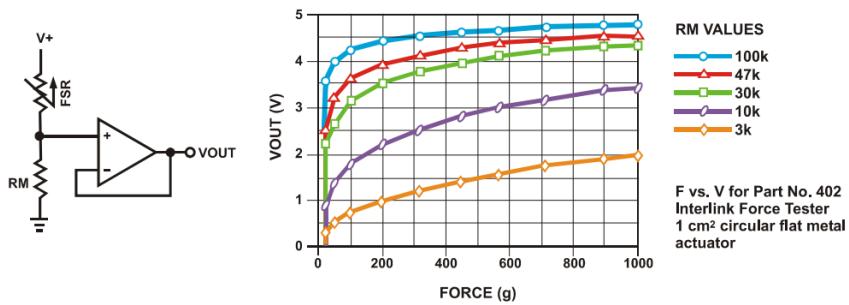


Figure 2.5: FSR Datasheet snippet

ments since their thickness keeps the size of the Pisa/IIT SoftHand reasonable for human-robot handshake. 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 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 allows 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 with measures standard of grams. As shown in [3], load cells can be used as 'ground truth' to calibrate force sensitive resistors to provide informations in Newtons. Using a *sensorized palm* developed in [5], sketched in Fig. 2.6 which embeds a load cell and placing the FSR sensors accordingly with the position of the sensors on the Pisa/IIT SoftHand; 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 position of the FSR sensors has been chosen accordingly to the position of the FSR sensors N.1 and N.2 on the Device 2. The experiment consist in applying a grasp to the device including not exclusively, the FSR sensors in the grasp. In post processing a model is fitted to the data and eventually allow the FSR to correctly estimate the grasping force.

The experiment is executed with a participant applying different forces on the above mentioned device, and recording the output from the FSR sensors and from the load cell of the *sensorized palm*. The plot in Fig. 2.8, shows the data obtain



Figure 2.4: FSR 13mm

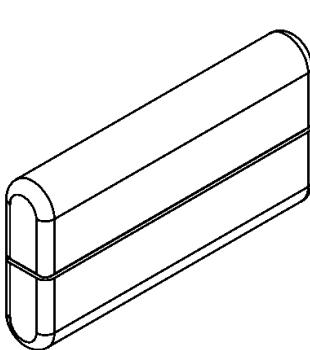


Figure 2.6: Sensorized palm

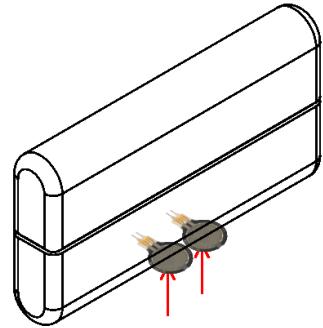


Figure 2.7: Sensorized palm with FSRs

from this experiment. Taking $N = 2$ as the number of FSR sensors installed on the Pisa/IIT SoftHand, $F_{fsr,i}$ as the measure of the generic $i - th$ sensor, the non calibrated grasping force is estimated as

$$\hat{F}_{fsr} = \sum_{i=1}^N F_{fsr,i} \quad (2.2)$$

A toolbox for data fitting from Matlab has been used in order to find the best fitting equation, that includes the origin, according to the Least Mean Square Error to the raw data, which analytically is:

$$F_{fsr} = 2.863 \cdot 10^{-9} \cdot \hat{F}_{fsr}^3 - 1.851 \cdot 10^{-5} \cdot \hat{F}_{fsr}^2 + 0.04863 \cdot \hat{F}_{fsr} \quad (2.3)$$

where \hat{F}_{fsr} is the value taken as the sum of the FSRs sensors, in this experiment two FSRs has been used. The variable F_{fsr} is returning Newtons and best explain the FSRs values with respect to the values of the *sensorized palm*.

Obviously, more advanced models can be fitted in order to have FSR sensors returning Newtons with a higher precision, but for the specific task required in this work is considered sufficient the fitted equation in 4.3. The handshake event is involving grasping forces in a limited range of forces, the fitted equation exists for $\hat{F}_{fsr} \in \mathbb{R}$, physical limitation of the hardware (max absorbed current)

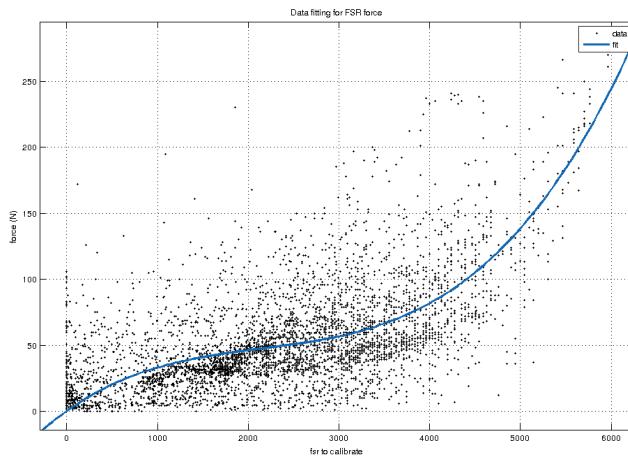


Figure 2.8: FSRs vs. Load Cell data

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 values in Newton and has 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 in this graph is the *Master*, which is managing all the messages in the system. Each node in order to send or receive messages to/from other nodes must communicate this 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 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 send data through 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 structure of messages are useful in order to send multiple message type over the same channel (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, in short a ROS node can be written as a C++ source file or as a python executable program.

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 inside a package 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, each one following the circuit diagram in Fig. 2.5; This allows the source code flashed on the Arduino to: read the voltage difference at FSRs terminals, publish the information to ROS. A specific protocol called *rosserial* is used in order to implement a ROS node with Arduino Uno.

3.2.3 Auxiliary nodes

The hardware related nodes of the project are now up and running, 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 provide 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 model. In these experiments human participants are intended to be a natural calibration system for the robot grasping force F_r . The hypothesis on participant's grasping force is shown in 4.1, participants are asked to apply the force that they are perceiving during the experiments.

$$F_h = F_r \quad (4.1)$$

this introduces a limitation on the evaluation of the data, in fact the equation is assumed to hold only in quasi-static systems. 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. 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 constraints on q introduced in 2.1 are valid through all this work since are hardware related. The *sensorized palm* is used in order to seek the force behaviour for values of the reference position $q > q_0$. The shells of the device are not deformable, due to the material used during the 3D printing. Increasing the reference position q of the Pisa/IIT SoftHand

squeezing the *sensorized palm* showed a linear relationship between the difference $q - q_0$ and F_r , i.e. **talk about why the spring relation is choosed**

$$F_r(q) = \begin{cases} k_r(q - q_0) & \text{for } q - q_0 \geq 0 \\ 0 & \text{for } q - q_0 < 0 \end{cases} \quad (4.2)$$

Where F_r is the force during the handshake applied by the robot on the participant's hand, q is the reference position sent to the device. During these experiment 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, Current, Real Position, Reference Position]. All the plots below are obtained as processing files with the previous structure. Each experiment starts with reference position set to 0 and finish with the reference position set to 0.

The experiments are in open loop so in order to avoid injuries an emergency function has been created, if the participant starts feeling pain the key 'x' on the keyboard must be pressed. The Pisa/IIT SoftHand will take as reference position 0 (fully open) and the whole program will be stopped. In case of emergency the file will be saved and the last data can be used to understand the configuration just before the trigger 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 Pisa/IIT SoftHand will not affect the FSR readings.

Participants

The participants to the experiments have been selected in an heterogeneous fashion from male to female with ages in (24-35 year old). Although the hand sizes

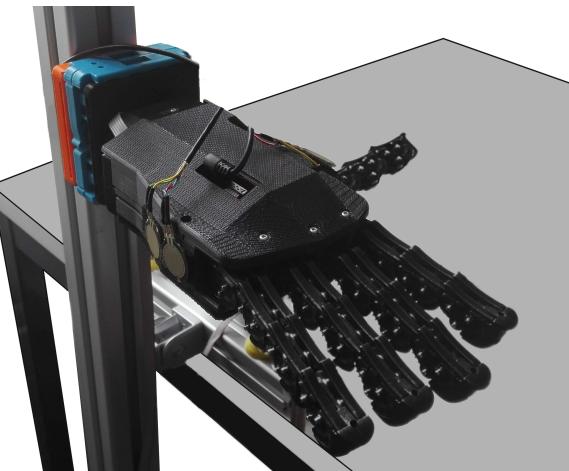


Figure 4.1: Palm facing down environment

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 4.2, therefore it is providing the methodology approach to this problem. Each participant is repeating each experiment five times, this provide useful information and allow to average the outcomes of the same participant.

4.1 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.

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

4.1.1 Description

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

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

the experiment lasts in total 6 seconds. A correlation between the reference position of the Pisa/IIT SoftHand and the values recorded from the FSRs is expected. The 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. 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. Although, this behaviour has been considered not consistent to fit, in post

processing, a model to the data, it can provide a first sight the relation q vs. F_h .

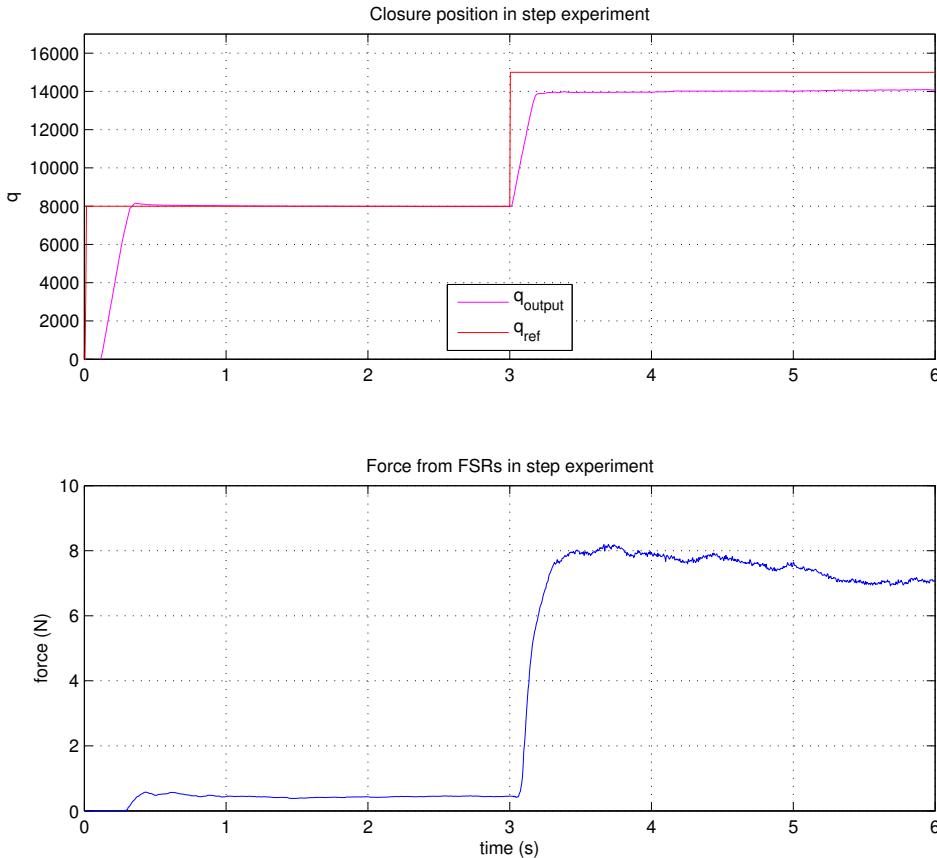


Figure 4.2: Step experiment in time

insert step experiment plots force vs q

4.1.2 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 suggest that a correlation between F_h and q exists. The Fig. ?? 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 during the handshake. 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. **to justify better the choice of 1 second can be implemented a function calculating the standard deviation for each cut transient (too much?)**

4.2 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 find the relationship between q and the force that the human apply on the sensors F_h using the assumption in 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 4, experiments are repeated multiple times but the method allow the participants to understand the behaviour of the Pisa/IIT SoftHand 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 next q of the Pisa/IIT SoftHand. 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 of each signal.

4.2.1 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 as from 2.1, is set as input to the Pisa/IIT SoftHand while the sensors are tracking the force F_h . The reason behind a pseudo-randomized sequence is used, can be

summarized in two important aspects:

- the steady state of $F_h(\hat{t})$ for a certain $q(\hat{t})$ can be influenced $q(\hat{t} - 1)$, and having a fully randomized sequence of q can highlight this behaviour,
- during the post processing procedure: having the exact same sequence of q along multiple experiments allow to elaborate the data just using the indexes.

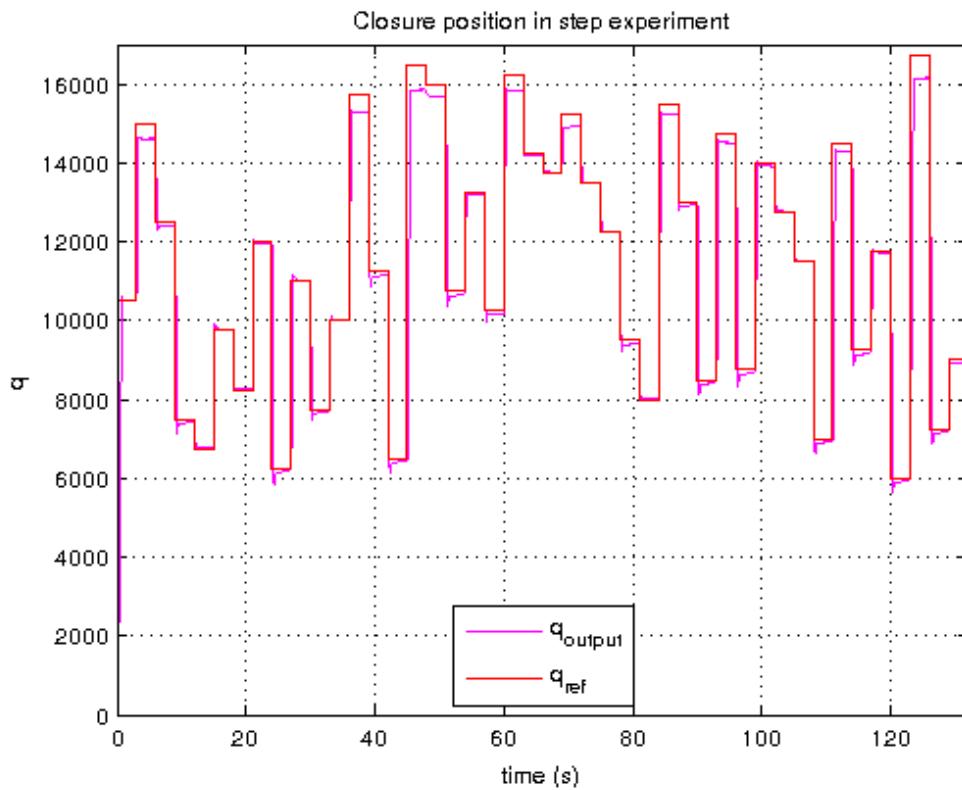


Figure 4.3: Pseudorandom experiment in time

A single experiment lasts 2'12", and the reference positions sent to the Device are randomized with a fixed seed and are unique, this means that if \hat{q} is transmitted for the first time at t_1 it is hold for 3 seconds and it won't be transmitted for the rest of the experiment. The participants response can be evaluated in the Fig. 4.4, where at a first sight a correlation with the 4.3 can be appreciated.

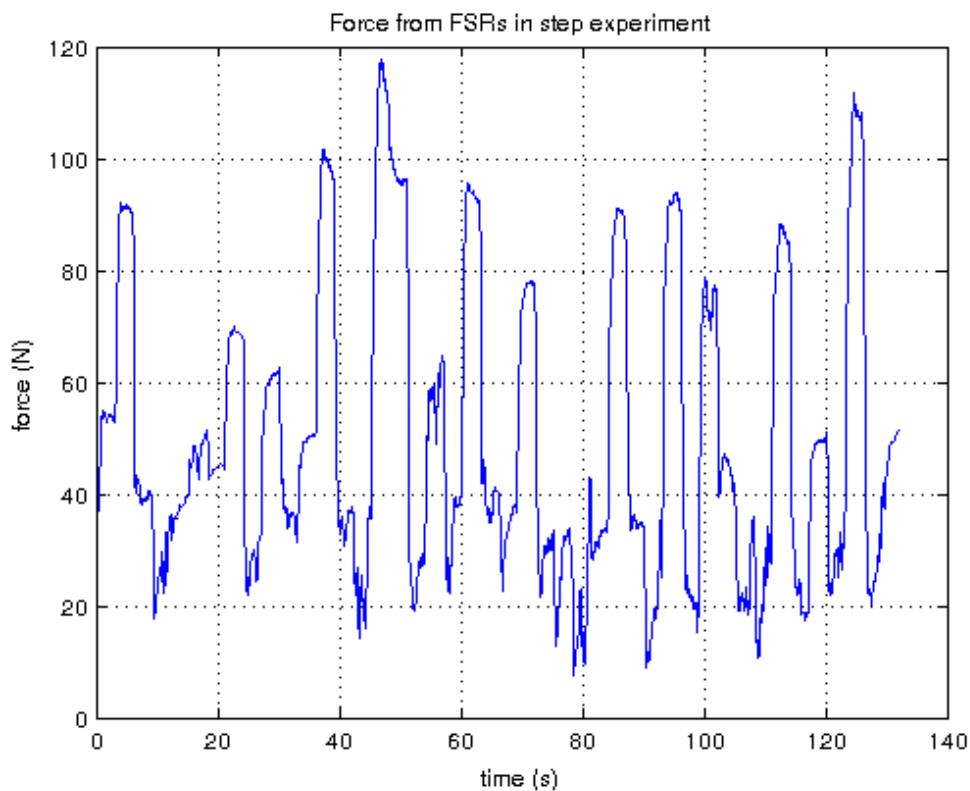


Figure 4.4: Pseudorandom experiment in time

A technique to filter the behaviours due to dynamics is needed and the same procedure described in 4.1.2 is used.

insert a plot of just random sequence of q ; insert a plot of sensors force behaviour; talk about the transient elaboration and explain how to find the model

Chapter 5

Closed Loop controllers

5.1 Empirical Proportional controller

5.2 Human-calibrated controller

Chapter 6

Results

Conclusion

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