Detecting human intention in
Physical human-robot interaction
FINAL THESIS
Detecting Human Intention in Physical human robot interaction

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Preface

This is the Msc. final thesis of Jochem Jonkman. This research is done from January till October 2009 and is a subsequent to my literature survey with the title “Light Disassembly”. This research is the first step in the development of one of the research topics of my direct supervisor Mustafa Suphi Erden, “physical human robot interaction”. I would like to thank him for his support and research suggestions during this period. Also I would like to thank professor Tomiyama for his intellectual support and research suggestions along the way.

To continue, for their great patience, help and supervision in designing and implementation of the LEM sensor technology in the robot electronics and repairing of the robot itself, done in the laboratory of systems and control, I would like to thank Ron van Puffelen and Kees Slinkman.

Finally I would like to thank to my parents after all these years for their continuous trust and financial support giving me the opportunity to finish my studies, and of course to Linda for her love and mental support.

Jochem Jonkman

Delft, October 14, 2009
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Abstract

Human assist robotic systems cooperate with human for performing a task. In human power amplifying systems, human and robot interact physically and the robotic arm augments the force of the human, while he still perceives a part of the mass of the controlled object. Human skill and robotic power are combined into one system and due to the human control a flexible robotic systems is obtained.

This research aims at detecting human intention in static physical human robot interaction, by observing the changes of manipulator joint torques, due to human interference, and translates these into an end point force vector called “human intention”. To avoid expensive 3D force sensors, an eddy current sensor technique is used to observe torque fluctuations in the joint actuators. This enables physical interaction from anywhere on the robot instead of solely to the tip, where the force sensor would be placed. The project includes designing a human-robot interface system, in which the position controlled robotic manipulator, is physically interacting with its human controller by adapting to his intended movements.
**Abbreviations / symbols**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3ME</td>
<td>Faculty of Mechanical, Maritime and Materials Engineering</td>
</tr>
<tr>
<td>A</td>
<td>Ampere</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>Dcsc</td>
<td>Delft centre for systems and Control</td>
</tr>
<tr>
<td>DZv</td>
<td>Dead zone threshold value</td>
</tr>
<tr>
<td>F_{HI}</td>
<td>Human intentional force vector</td>
</tr>
<tr>
<td>H.A.R.S.</td>
<td>Human Assist Robot Systems</td>
</tr>
<tr>
<td>HARDIS</td>
<td>Human assist robot for disassembly</td>
</tr>
<tr>
<td>HI</td>
<td>Human Intention</td>
</tr>
<tr>
<td>Hri</td>
<td>Human-robot interaction</td>
</tr>
<tr>
<td>LEM</td>
<td>Company name</td>
</tr>
<tr>
<td>M</td>
<td>Magnitude</td>
</tr>
<tr>
<td>mV</td>
<td>milliVolt</td>
</tr>
<tr>
<td>Ncm</td>
<td>Newton centimetre</td>
</tr>
<tr>
<td>Phri</td>
<td>Physical human-robot interaction</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of freedom</td>
</tr>
<tr>
<td>RRR</td>
<td>Three rotational joints</td>
</tr>
<tr>
<td>K_{t}</td>
<td>Torque constant</td>
</tr>
</tbody>
</table>
1 Introduction

In the near future human and robot will be working side by side in the same workspace performing tasks together. Human robot interaction (Hri) is necessary for communication and the control of the system. Interaction on a physical level provides a powerful technique for the human controller to give instructions to the robot. Robotic systems that assist and cooperate with the human enable task sharing that necessitate both human and robot involvement. A driving force for the research and development on physical human robot interaction (Phri) is the demand for flexible robotic systems in industry.

1.1 Motivation

Robotic systems of nowadays are mainly used for single purpose tasks within well-defined environments and reference frames and therefore being suitable for mass production. In industry there’s a need for robotic systems able to adjust quicker to the changing working environments, varying complex tasks and to operate within unconstrained environments. Development of robot technology able to cope with a wide range of processes, tasks and objects drives the emphasis towards flexibility and adaptability. It is recognized that human robot cooperation is the key to achieve this, as it combines human and robotic qualities into one system. Humans are well known for their flexibility and adaptability, decision-making, anticipative power and recognition. Robot qualities are physical power, precision and invulnerability. The combination, with the human as central supervisory control organ, results in a flexible robotic system.

The research field of human robot cooperation emerged into a new group of robotic systems, called Human Assist Robot Systems (H.A.R.S.).
1.2 H.A.R.S

H.A.R.S. are robotic systems where the human’s intellect, skill & knowledge is combined with strength & invulnerability of robots to get optimal properties for working in complex, dangerous or hazardous open industrial environments. These hybrid systems integrate human and robotic qualities into one robotic system that has the ability to work within unconstrained workspaces. By enabling the human to be the central control organ, the need for fully autonomous robots is eliminated. H.A.R.S. assist a worker, based on human-machine interaction, in a task they are both taking actual part in. To achieve effective and flexible use of robot assistants interfacing in a human friendly and safe way is obliged. A natural and intuitive way of working and interaction is important to create this close teamwork. Current H.A.R.S. technologies are: Cobots (cooperative robots), Tele-operated robotics and Power amplifying robots. In general for human force augmenting cooperative robotic systems, human intervention, force & visual feedback and physical interaction are integrated into one system.

This research is concerned with the power amplifying technologies as it involves physical human robot interaction. The Extender technology from Kazerooni (Berkley University) is the pioneering technique within this area (Fig. 1-2). Physical contact and force sensing facilitate transfer of mechanical power and information signals. Interfacing on a physical level and force feedback to the human regarding the manipulated load makes it possible to interact with the robot.

Load sharing, force signal communication and human force augmentation are the main principles of the power amplifying technology, to provide cooperative manipulation tasks.
1.2.1 Force sensor drawbacks

The use of force sensors has a couple of drawbacks. The sensors are placed at a specific point on the manipulator. This results in the infeasibility to detect collisions that occur on any part of the structure. Therefore, physical interaction is also bounded to the point where the sensor is placed. This limits the flexibility of the overall human-robot interaction.

Some other drawbacks are the high prices of force sensors and their receptiveness for noisy environments and high temperatures. In force sensor based manipulator control force feedback is obtained by amplifying the strain of the sensors which contains amplified noise as well\(^\text{12}\). The soft mechanical structure of force sensors and their narrow bandwidth makes them sensitive to high frequency disturbances affecting the end-effector’s control\(^\text{13}\). In an unstructured industrial environment like a complete car disassembly plant a force control system of a manipulator must be able to deal with various vibrations and force impact disturbances.

1.2.2 Human Assist Robot System for Disassembly (HARDIS)

HARDIS\(^2\) is a conceptual design and has been developed within the Intelligent Mechanical Systems research group of 3ME. It is a human assist robot system that cooperates with the human worker in the manual disassembly phase of obsolete products like end-of-life vehicles. This phase involves power demanding and repetitive tasks and necessitates intense human labour\(^\text{14}\). It instigates implications for ergonomics causing back disorder problems and seriously influences the quality of life of the
However, the human worker is indispensable from the job as his perception, flexibility, decision-making, skill and experience are essential. HARDIS is a mobile, statically balanced position controlled manipulator that compensates human with power and speed in end of life car disassembly tasks (Fig. 1-3). The aim of the force control of the system is, to integrate a force sensing system that uses no force sensors.

1.3 Boundaries /scope

The focus in this project points to the collaborative way of human control in which the human communicates with a robotic manipulator by physical interaction. To enable this, the robot should understand from human impact what the human’s intentions are. So a disturbance applied by human interaction to the position controlled robot will be interpreted as an information signal that includes the human’s intention. To measure this, a 3 dimensional force sensing technique will be applied.

In contrast to the current power amplifying techniques, where expensive force sensors are used, a cheap eddy current sensor technique is utilized for estimating the human exerted forces. Apart from being cheap, this technique has the big advantage that interaction can be done anywhere on the manipulator instead of solely to the tip, where normally the force sensor is placed in the extender technology.

The first step in development of the HARDIS concept is done in this thesis and implies that physical interaction between human and robot will take place in stationary state of a position controlled robotic arm. The robot in use is a statically balanced robotic arm and therefore mass and gravitational terms regarding the manipulator will not affect the measurement. The interaction information will be translated into a path update of the end point of the robot. Due to the fact that the interaction takes place at stationary state, dynamical behaviour of the robot can be neglected in the measurement.
1.4 Research goal / project description

In this research a Phri interface is designed in a Matlab/ Simulink control software environment and applied into a real system that involves a planar robotic arm. It contains a system design and control design including position and motion control of a robotic arm depending on the system’s state. The aim is to observe and detect human intention in physical cooperation with a position controlled robotic manipulator, by measuring armature current fluctuations of the joint actuators caused by human interference. The detected human intent is translated into a path update coordinate and in that way the human determines the trajectory the robotic arm following. The research goal can be defined as follows:

*Design and create a human-robot interface system, in which a position controlled robot arm is physically interacting with its human controller by adapting its position to his intended movements.*
2 Human Intention

In Phri the robot arm receives real-time commands of control from the human. These commands are communicated to the robot by physical touch pushing it in the desired direction. The human exerts a force somewhere on the manipulator and wants the robot to update its end-effector position in the direction of pushing. In this way the human lets the robot move along a desired trajectory in space.

Human intention (HI) can be defined as the applied force by the human on the manipulator projected to the end-point of the arm (Fig. 2-2). This force has a certain magnitude (M) and direction in 3 dimensional space. These two factors determine the human intentional force vector (F_{HI}). This vector contains the information of how far the controller wants the end-effector to move, based on M, and in which direction (Fig. 2-3).

The robotic arm is position controlled and as a result its actuators are continuously activated. Human intervention will cause a disturbance to the joint torques of the manipulator, because the robot controls to maintain its position (Fig. 2-4). The joint torque fluctuations are measured (§ 3.4) and the torque vector \([\Delta \tau_1, \Delta \tau_2, \Delta \tau_3]\) can be translated into the end point force \([F_{HI}]\) by using the Jacobian matrix belonging to the robot arm (§ 4.3).
2.1 Position update

To update the position of the robot’s end-point, $F_{HI}$ needs to be estimated; therefore a 3 dimensional force measurement is required.

2.1.1 3D force measurement

Conventional 3D force measurement involves expensive sensors built with strain gauges. However, in case of dc motor actuation, joint torque measurements can be used to estimate the external force. Joint currents can be measured with eddy current sensors.

2.1.2 Follow the human intended path

The force $F_{HI}$ is used to update the trajectory the human wants the robot’s end-point to follow. By the human applied force, the robot is guided to an end-point $P$ displacement in space, which is based on the intention and the direction of the force. The human pushes against the robot resulting in a slight joint angle error. The robot is position controlled and pushes back against the human with the same force to control the end-point back to the reference position. The generated joint torques are measured and translated to an end-point force called $F_{HI}$. This force is used to determine the next coordinate and the system updates to it like in the figure (Fig. 2-5).

![End Point [P]](image)

**Fig. 2-4: Path update**
3 System Setup

The system setup on which the interface is applied is discussed in this chapter. During the project the following steps are taken to complete the research set-up on which the interface system could be tested and run.

3.1 Signal Flow

The hardware components used in the system are the “Edro” robotic arm, a data acquisition (DAQ) module and a desktop PC. The communication signal flow between these components is shown in the diagram (Fig. 3-2). The joint angles are read by the PC from the angle encoders at the joints. Via the serial port (RS232) interface the angle signals are imported.

The DAQ system is used to read the armature currents from the current sensors and feed them to the PC. The Phri interface is running on the computer, powered by the Matlab and Simulink control software. The manipulator is controlled via an RS232 serial port connection. Additional, the armature currents are read into Matlab through USB to complete the control task in the control algorithms. From the PC motor voltage is the control signal to the Edro joint actuators.
3.2 Edro

The robotic arm used in this research is the educational robot (Edro), which is mainly used in the 3ME bachelor mechatronics project and for several research topics at the Delft Center for Systems and Control (Dcsc). Edro has 6 DOF and is actuated with 5 revolute joints in the base, shoulder, elbow, wrist and wrist rotation and a translational gripper joint (Fig. 3-3). An additional current sensor is placed in the gripper for force sensing. The upper arm link is approximately statically balanced on the elbow joint, due to weight compensation. Two internal springs at the shoulder joint compensate for gravitational forces acting there. The manipulator can maintain position without actuation and is therefore assumed to be statically balanced.

The Edro is used to represent the HARDIS manipulator. The physical human-robot interaction takes place at the second link of the arm. Up to that place the robot covers 3 DOF, namely the base, the shoulder and the elbow rotations. The end-effector rotations and gripping have no influence on this interaction. The Edro is therefore used in a similar way as a two link arm with three rotations like in figure 3-3. Point P is placed in the wrist joint axis. The two remaining rotations (wrist, wrist rotation) and the gripper translation are assigned to the end-effector. Point P is the
connection between the 3 DOF manipulator and the end-effector (Fig. 3-4). Physical interaction takes place anywhere on the arm until P. The estimated human intentional force will be translated to this point. The length of link 1 and link 2 is 0.25 m and the origin of the global reference frame is placed in the shoulder joint.

The base, the shoulder and the elbow joint of the Edro are actuators to be controlled for this research setup. The joints are actuated with modified dc servo motors with encoders to measure the joint angles. To translate the encoder angles into degrees and radians the following encoder conversion table (Tab. 3-1) is used, which is result from test measurements.

<table>
<thead>
<tr>
<th>Joint</th>
<th>encoder</th>
<th>Degrees (°)</th>
<th>Radians</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>240</td>
<td>57.2958</td>
<td>1</td>
</tr>
<tr>
<td>Shoulder</td>
<td>240</td>
<td>57.2958</td>
<td>1</td>
</tr>
<tr>
<td>Elbow</td>
<td>360</td>
<td>57.2958</td>
<td>1</td>
</tr>
</tbody>
</table>

Tab. 3-1: Encoder angle conversion

3.3 Communication

Via the RS232 serial port interface the pc communicates and controls the Edro. Matlab and Simulink software is used for the communication. The files to enable the RS-232 serial port communication with the Edro through Matlab were gathered from at Dcsc. This code handles opening and closing of the port and the processing and communication of the joint angles from and motor voltage to the robot. In Simulink a model is developed for the interface, containing the matlab functions and signal processing (Ch 6). For the motion and position control of the arm a proportional controller is acquired from Dcsc.
3.4 Joint torque measurement

To establish the 3D force measurement that measures the joint actuation currents, the Edro electronic control circuit had to be adjusted with additional current sensors. Testing and designing of the circuit as well as the implementation of the new sensor board is done with supervision of technical support people.

3.4.1 LEM current sensors

The armature current sensors used in the setup, LEM eddy current transducers\textsuperscript{16} from the company LEM, measure the current using the Hall effect\textsuperscript{17}. The magnetic field (B) around the wire created by the flowing current (i) is concentrated in a magnetic circuit and measured in the air gap using a Hall device (Fig. 3-5). The advantage, compared to measuring current using a small resistor, is the negligible amount of voltage drop across the sensor. The output of the transducers fed to the DAQ is given in voltages. These voltages represent the amount of torque measured. Test measurements on the setup in the electronics lab point out that the measuring ratio of the LEM current transducers is 150 mV/A.

3.4.2 Joint torques

The joints are driven by DC motors. The torque (τ) of DC motors is linearly proportional to the armature current (i) by the motor torque constant (K_t)\textsuperscript{18}:

\[ \tau = K_t \times i \]
To determine the Kt values of the dc motors, the system is approached as a black box of which the output is linked to the input by Kt. The input of the system is a known real applied torque to the motor. The output of the system is a measured current value. The torque constants are separately determined per dc motor. They are calibrated for an applied torque that lies within the measuring range of the joint. The applied torque leads to a current rise in the dc motor to generate a motor compensational torque. Hence, the applied torque is equal to the motor torque. The current fluctuation (Δi) is measured. For the base joint torque of 3 Nm is used to determine Kt. It is applied to the motor leading to a fluctuation in current measured by the current sensor as shown in an example below (Fig. 3-5).

![Current sensing plot](image)

**Fig. 3-5: Current fluctuation in the base joint to compensate for an applied 3Nm torque**

The real current fluctuation Δi is determined by dividing the sensor value through the measuring ratio of the sensor of 150 mV/A. The sensor value of 0.3857 then gives a Δi of 2.5713 A. The torque constant for the base joint is determined by dividing the applied torque through the current fluctuation: $K_t = \frac{\tau}{\Delta i}$. A series of measurements with a 3.0 Nm torque resulted in a torque constant for the base joint dc motor of, $K_t = 1.16$. The same procedure is done for the shoulder and elbow joint resulting in the next motor torque constant table (Tab. 3-2).
### Tab. 3-2: Motor torque constants

<table>
<thead>
<tr>
<th>Joint</th>
<th>Applied torque [Nm]</th>
<th>Sensor value [V]</th>
<th>∆i [A]</th>
<th>Ki</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>3</td>
<td>0.3857</td>
<td>2.5713</td>
<td>1.16</td>
</tr>
<tr>
<td>Shoulder</td>
<td>5</td>
<td>0.2708</td>
<td>1.81</td>
<td>2.76</td>
</tr>
<tr>
<td>Elbow</td>
<td>3.5</td>
<td>0.2173</td>
<td>1.49</td>
<td>2.349</td>
</tr>
</tbody>
</table>

The accuracy of the system based on these torque constants is examined for a couple of force estimations done by the interface. A 3D force with a known magnitude in an arbitrary direction is applied to the manipulator (\(M_{F,\text{applied}}\)). The manipulator is at initial position and measurement results in an estimation of this force magnitude (\(M_{F,\text{estimate}}\)). Four estimations are listed below (Tab. 3-3) and they all give an \(M_{F,\text{estimate}}\) within 90% accuracy of \(M_{F,\text{applied}}\). This only gives an indication of the real accuracy of the system.

### Tab. 3-3: Force magnitude estimation series

<table>
<thead>
<tr>
<th>(M_{F,\text{applied}}) [N]</th>
<th>(F_x) [N]</th>
<th>(F_y) [N]</th>
<th>(F_z) [N]</th>
<th>(M_{F,\text{estimate}}) [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.5</td>
<td>-8.805</td>
<td>-12.96</td>
<td>-8.81</td>
<td>19.97</td>
</tr>
<tr>
<td>15</td>
<td>-3.395</td>
<td>0</td>
<td>15.691</td>
<td>16.05</td>
</tr>
<tr>
<td>23</td>
<td>-5.56</td>
<td>-14.78</td>
<td>-14.81</td>
<td>22.64</td>
</tr>
<tr>
<td>16</td>
<td>-7.25</td>
<td>0</td>
<td>15.99</td>
<td>17.55</td>
</tr>
</tbody>
</table>

### 3.4.3 Data acquisition

To read the data from the current sensors and use it as input for the interface the National Instruments NI-USB-6008\(^1\) data acquisition module is integrated in the set-up (Fig. 3-7). It is a 12 bit module and converts the analog voltage signal from the LEM sensors into a digital signal to the PC.
The number of bits of the converter represents the resolution of the digital signal. The DAQ module sends a 12-Bit signal to the computer, which means that the analog voltage signal is divided in $12^2 = 4096$ steps. The LEM has a reference output voltage ($V_{\text{ref}}$) of 2.5 V and an output range of approximately [0, –5] V. The smallest interval into which the output signal range is divided is $5 \text{ V} / 4096 = 2.1 \times 10^{-3} \text{ V}$. The motors draw a maximum current of [-3, +3] Ampere. The current sensor measuring rate of 150 mV/A results in a measuring range of [-450, +450] mV. The complete current sensing / data acquisition part of the system seems to be sufficient. The current fluctuations in the motors can measured up to every 0.014 A.
4 Kinematic Modeling

A kinematic model is sufficient to study the relationship between a robot’s joint variables values and the resulting position of the robot links and end-effector. A joint link analysis is done to define the model as a chain of links and joints and in the next paragraph the corresponding transformation matrix is created. Then the inverse kinematics of the model is assessed. Finally the Jacobian matrix is determined as it defines the relation between joint moments and end-effector force in three dimensional space. The figure below shows the joint-link model of the Edro used for the analysis.

![Edro joint-link model](image)

**Fig. 4-1: Edro joint-link model**

4.1 Joint link analysis

The tool or end-effector of the manipulator is required to follow a trajectory to manipulate objects or carry out the task in the 3D workspace. This necessitates control of position of each link and joint of the manipulator.

The kinematic model describes joint and link spatial positions as well as end effector position. A robotic arm can be described as a chain of links
interconnected by joints allowing revolute motion between these links. A link is defined as a rigid body and each joint exhibits one degree of freedom (DOF).

The amount of degrees of freedom a manipulator has is the quantity of independent parameters necessary to entirely give its position and orientation in space. Since every joint has only one degree of freedom, the degrees of freedom of a manipulator are identical to the number of joints. The Edro is modeled as a 3-DOF chain of rigid links connected by revolute joints (Fig. 4-2). A coordinate frame \( \{i\} \) will be connected to every link \( i \), describing the position and orientation of each link in space. The homogeneous transformation matrix describes the relation of the position and orientation of frame \( \{i\} \), relative to the forgoing frame \( \{i-1\} \) (§ 4.1.1). A 1-DOF joint necessitates only one variable to define its position. The revolving displacement of the joint is measured by angle \( \theta_i \). The joint displacement for a revolute joint is shown in Fig. 4-3.

![Fig. 4-2: 1 DOF joint link connection](image)

For a revolute joint the angle \( \theta \) varies, describing the relative position of links. This parameter is defined as the joint variable. A generalized parameter \( q_i \) is used to denote the joint displacement, \( q_i = \theta_i \).

Two types of kinematics are recognized to couple joint-link parameters to end point position coordinates, namely direct and inverse kinematics.
Direct kinematics: For a known set of joint angles, determine the end-effector’s position and orientation relative to the manipulator’s inertial reference frame.

Inverse kinematics: For a known position and orientation of the end-effector, determine with respect to an inertial reference frame the set of joint angles that brings the end-effector there.

Manipulator control involves both direct and inverse kinematic models of the manipulator. The block diagram shows the interconnection between the models (Fig. 4-4).

The task to be carried out by the robot is acknowledged in terms of the end-effector coordinates in space. The joint angles needed to carry out the task are computed using the inverse kinematic model. To determine the end-effector position in space, at any instant, the joint angles are entered in the direct kinematic model.
4.1.1 Transformation matrix

To analyze the motion of the robot to each link of the manipulator starting from the base to the end-effector a single frame is assigned for the kinematic modeling (Fig. 4-6). The homogeneous transformation matrices relating the frames attached to following links describe the spatial relationship between neighboring links. The composition of the separate homogeneous transformation matrices resolves the overall transformation matrix, describing end-effector frame with respect to base frame.

The Edro is modeled as a 3 DOF planar manipulator with three revolute joints that is an RRR arm configuration (Fig. 4-5). The axes of joint 2 and joint 3 are parallel and axis of joint 1 is perpendicular to these two. At the end point of the arm an end effector is attached.

To determine the “End point” transformation matrix, the frames are assigned in the following manner, shown in the frame assignment (Fig. 4-6). This is done according to the Denavith-Hartenberg (DH) convention\textsuperscript{20}. 

*Fig. 4-4: RRR arm configuration*
The resulting DH joint-link parameters are tabulated in Tab. 4-1. For all the three joints the joint-offsets are assumed to be zero.

<table>
<thead>
<tr>
<th>Link</th>
<th>ai</th>
<th>αi</th>
<th>di</th>
<th>θi</th>
<th>qi</th>
<th>Cai</th>
<th>Sai</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>90°</td>
<td>0</td>
<td>θ1</td>
<td>θ1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>L2</td>
<td>0</td>
<td>0</td>
<td>θ2</td>
<td>θ2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>L3</td>
<td>0</td>
<td>0</td>
<td>θ3</td>
<td>θ3</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Tab. 4-1: Joint-link DH parameters for the assigned frames

The link transformation matrices are

\[
^0T_1(\theta_1) = \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

\[
^1T_2(\theta_2) = \begin{bmatrix} C_2 & -S_2 & 0 & L_2C_2 \\ S_2 & C_2 & 0 & L_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]
\[
2T_3(\theta_i) = \begin{bmatrix}
C_3 & -S_3 & 0 & L_2C_3 \\
S_3 & C_3 & 0 & L_2S_3 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

With, \( C_i = C\theta_i = \cos\theta_i \), and \( S_i = S\theta_i = \sin\theta_i \)

The overall transformation matrix for the endpoint of the arm is, therefore,

\[
0T_3 = 0T_3T_2T_3 = \begin{bmatrix}
C_1S_23 & -C_1S_23 & S_1 & C_1(L_3C_23 + L_2C_2) \\
S_1C_23 & -S_1S_23 & -C_1 & S_1(L_3C_23 + L_2C_2) \\
S_{23} & C_{23} & 0 & L_3S_{23} + L_2S_2 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

With, \( C_{ij} = C(\theta_i + \theta_j) = \cos(\theta_i + \theta_j) \) and \( S_{ij} = S(\theta_i + \theta_j) = \sin(\theta_i + \theta_j) \)

The joint link parameter set for the assigned frames in table (Tab. 4-1) belong to the zero home position of the manipulator. This is the configuration where all the joint variables are assumed zero, \( \theta_1 = \theta_2 = \theta_3 = 0 \). This is not a physically achievable configuration and therefore an alternate home position is required. For the Edro this alternate initial position is shown below (Fig. 4-7). To this position the robot is calibrated.

![Fig. 4-6: Home position Edro](image)
The new joint displacement $\theta_2$ and $\theta_3$ are defined by adding $+90^\circ$ to joint angle $\theta_2$ and $-90^\circ$ to joint angle $\theta_3$, tabulated in table

<table>
<thead>
<tr>
<th>Link</th>
<th>$a_i$</th>
<th>$a_i$</th>
<th>$d_i$</th>
<th>$\theta_i$</th>
<th>$q_i$</th>
<th>$C_{a_i}$</th>
<th>$S_{a_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>$90^\circ$</td>
<td>0</td>
<td>$\theta_1$</td>
<td>$\theta_1' = \theta_1$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>$L_2$</td>
<td>0</td>
<td>0</td>
<td>$\theta_2'$</td>
<td>$\theta_2' = \theta_2 + 90^\circ$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>$L_3$</td>
<td>0</td>
<td>0</td>
<td>$\theta_3'$</td>
<td>$\theta_3' = \theta_3 - 90^\circ$</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Tab. 4-2: Home position DH joint link parameters

### 4.2 Inverse Kinematics

Inverse kinematics is used to determine the joint angles ($\theta_1$, $\theta_2$, $\theta_3$) as function of the end effector’s position vector. A geometric solution is created by using the manipulator geometry and the end point coordinates $(x,y,z)$. The $(x,y)$ coordinates of the end effector define $\theta_1$ (Fig. 4-8).

$$\theta_1 = A \tan 2(y,x), \quad \text{with} \quad u = \sqrt{x^2 + y^2}$$

![Fig. 4-7: Model top View](image)
As the Edro is a planar robot $\theta_2$ and $\theta_3$ are determined in the 2D configuration of the $X_0Z_0$ plane (Fig. 4-9). $u$ and $z$ are extracted from the transformation matrix:

\[ u = L_2 C_2 + L_3 C_{23} \]
\[ z = L_2 S_2 + L_3 S_{23} \]

We can apply the law of cosines to solve for $\theta_3$:

\[ r^2 = z^2 + u^2 = L_2^2 + L_3^2 - 2L_2L_3 \cos(\pi + \theta_3) \]

Since

\[ \cos(\pi + \theta_3) = -\cos \theta_3 \]

We have

\[ \cos \theta_3 = C_3 = \frac{u^2 + z^2 - L_2^2 - L_3^2}{2L_2L_3} \]
The computational algorithm to verify existence of solutions should check the condition

\[ L_2 + L_3 \geq \sqrt{u^2 + z^2} \]

Assuming that the solution exist it lies the range of

\[ \pi \leq \theta_3 \leq 0 \]

The other possible solution may found by

\[ \theta'_3 = -\theta_3 \]

By definition

\[ \theta_2 = \beta - \varphi \quad , \quad (\theta_3 > 0) \]

Defining \( \beta \) as a function of \( x \) and \( y \)

\[ \beta = A \tan 2(u, z) \]

Applying the law of cosine to find

\[ \cos \varphi = \frac{u^2 + z^2 + L_2^2 - L_3^2}{2L_2 \sqrt{u^2 + z^2}} \quad , \quad \text{note: } 0 \leq \varphi \leq \pi \]
4.3 System Jacobian

The connection between the joint torques and the end-point force vector is obtained via the *principle of virtual work*. This is utilized to determine the joint torques needed to exert a certain end-effector force\(^{21}\).

Torque \(\tau_i\), acting on joint \((i)\), causes an infinitesimal joint displacement \(\delta q_i\), therefore \(\delta q\) is the \(n \times 1\) infinitesimal joint displacement vector. These virtual displacements of a mechanical system need only satisfy the set of kinematic constraints. An infinitesimal end-point displacement \(\delta p\) is also produced by the end-point force \(F\) that acts on the mechanical system. The virtual work \(\delta W\) caused by the torques and the force is given by the following equation.

\[
\delta W = \tau^T \delta q - F^T \delta p
\]

\[\text{(1)}\]

The principle of virtual work is valid for a system in equilibrium. The joint torques are the net torques that balance the endpoint force \(F\). During static interaction on the statically balanced arm the joints are assumed to be frictionless.

From (1), the Jacobian \(J\) relates infinitesimal joint displacement \(\delta q\) to infinitesimal end-effector displacement \(\delta p\) as:

\[
\delta p = J(q)\delta q
\]

\[\text{(2)}\]

Substituting (2) into (1) and rearranging gives

\[
\delta W = (\tau - J(q)^T F)^T \delta q
\]

\[\text{(3)}\]

According to the principle of virtual work the manipulator mechanism is in static equilibrium, if and only if, the net virtual work is zero for arbitrary virtual displacements, that is,
\[ \delta W = 0 \]  \hspace{1cm} (4) 

Substituting it in (3), leads to the result

\[ \tau = J(q)^T F \]  \hspace{1cm} (5)

Where \( \tau \) is the vector of joint torques \( (\tau = \tau_1, \tau_2, \ldots, \tau_n)^T \) and \( J^T \) is the transpose of the Jacobian matrix that relates infinitesimal joint displacement \( \delta q \) to infinitesimal end-effector displacement \( \delta p \).

Equation (5) states that the transpose of the Jacobian matrix and transforms the end-effector torque to the corresponding joint torques.
4.3.1 Edro Jacobian

The Jacobian of the Edro is determined for a 3 DOF planar robot arm (Fig. 4-10). Each column of the Jacobian matrix is computed separately and all the columns are combined to form the total Jacobian matrix. The joint displacements $\theta_1$, $\theta_2$ and $\theta_3$ are shown in the figure and the transformation matrices are given in §4.1.1.

![Fig. 4-9: 3 DOF planar robot arm](image)

The Jacobian matrix column $J_1$ for joint 1, which is a rotary joint, will be determined next.

In theory the Jacobian for a revolute joint is given by\textsuperscript{22}:

\[
J_1(q) = \begin{bmatrix} P_{i-1}x^{i-1}P_n \\ P_{i-1} \end{bmatrix}
\]
In which $P_{i-1}$ is the joint axis vector and $^{i-1}P_n$ the position vector. The joint axis vector $P_0$ (for $i = 1$) is the vector in frame $\{0\}$ which describes the axis of rotation of joint 1.

$$P_0 = ^0R_0 \hat{n}$$

The transformation matrix $^0T_0$ and rotation matrix $^0R_0$ are the identity matrices. Thus,

$$P_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

The origin of frame \{n\} at the end-effector is $O_n = [0 \ 0 \ 0 \ 1]^T$, this applies for any frame i.e. for any value of n. The end-effector position vector (for $i = 1$ and $n = 3$) is defined as:

$$^0P_3 = ^0T_n O_n - ^0T_0 O_n \quad \text{or} \quad ^0P_3 = ^0T_3 - ^0T_0$$

Substituting the transformation matrix $^0T_3$ in above equation gives

$$^0P_3 = \begin{bmatrix} C_1C_{23} & -C_1S_{23} & S & C_1(L_3C_{23} + L_2C_2) \\ S_1C_{23} & -S_1S_{23} & -C & S_1(L_3C_{23} + L_2C_2) \\ S_{23}C_{23} & 0 & L_2S_{23} + L_2S_2 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} - \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

Or
The first column of Jacobian, \( J_1 \), is computed by substituting (7) and (8) in the theoretical Jacobian for revolute joints. Thus,

\[
0 \cdot P_3 = \begin{bmatrix}
C_1 (L_0 C_{23} + L_2 C_2) \\
S_1 (L_0 C_{23} + L_2 C_2) \\
L_2 S_{23} + L_2 S_2 \\
0
\end{bmatrix}
\]

\( (8) \)

\[
J_1 = \begin{bmatrix}
0 & C_1 (L_0 C_{23} + L_2 C_2) & -S_1 (L_0 C_{23} + L_2 C_2) \\
0 & S_1 (L_0 C_{23} + L_2 C_2) & C_1 (L_0 C_{23} + L_2 C_2) \\
1 & L_2 S_{23} + L_2 S_2 & 0
\end{bmatrix}
\]

\( (9) \)

By following the similar steps for joint 2 and joint 3, \( J_2 \) and \( J_3 \) are obtained as

\[
J_2 = \begin{bmatrix}
-C_1 (L_0 S_{23} + L_2 S_2) \\
-S_1 (L_0 S_{23} + L_2 S_2) \\
L_0 C_{23} + L_2 C_2 \\
S_1 \\
-C_1 \\
0
\end{bmatrix}
\]

\( (10) \)

\[
J_3 = \begin{bmatrix}
-L_2 C_1 S_{23} \\
-L_2 S_1 S_{23} \\
L_0 C_{23} \\
S_1 \\
-C_1 \\
0
\end{bmatrix}
\]

\( (11) \)

Combining the three columns, the total Jacobian matrix for the Edro arm is
4.3.2 Static forces in 3-DOF planar robot arm

A force $F$ is applied on the end-effector of the 3-DOF articulated arm. The arm is position controlled and therefore in static equilibrium maintaining its position. To determine the force vector applied by the human assume that the force $F$ is acting at the origin of frame $\{3\}$ (Fig. 4-10) and is given by

$$F = \begin{bmatrix} f_x & f_y & f_z \end{bmatrix}^T$$

(13)

In General the vector $F$ is $6 \times 1$ Cartesian force-moment vector including also the applied torsions to the joints. This research is not concerned with these torsions and therefore the $F$ vector is a $3 \times 1$ force vector. Hence, the jacobian becomes a $3 \times 3$ matrix. The endpoint force depends on the joint torques in the following manner,$^2$ where $(J^T)^{-1}$ is the inverse of the transverse Jacobian matrix.

$$F = \left( J(q)^T \right)^{-1} \tau$$

(14)

The equation is valid when the chain is a non-singular configuration, i.e. if it is not completely extended or flexed. (14) provides a convenient tool for establishing a relation between the joint moments and the human intentional force exerted on the end point of the manipulator. The transpose of the obtained Jacobian is:
\[
J^* = \begin{bmatrix}
-S_1 (L_2 C_{23} + L_3 C_2) & C_1 (L_2 C_{23} + L_3 C_2) & 0 \\
-C_1 (L_3 S_{23} + L_2 S_2) & -S_1 (L_3 S_{23} + L_2 S_2) & L_3 C_{23} + L_2 C_2 \\
-L_3 C_1 S_{23} & -L_3 S_1 S_{23} & L_3 C_{23}
\end{bmatrix}
\quad (15)
\]

Substituting (13) and (15) in (14) gives

\[
\tau = \begin{bmatrix}
-S_1 (L_3 C_{23} + L_2 C_2) & C_1 (L_3 C_{23} + L_2 C_2) & 0 \\
-C_1 (L_3 S_{23} + L_2 S_2) & -S_1 (L_3 S_{23} + L_2 S_2) & L_3 C_{23} + L_2 C_2 \\
-L_3 C_1 S_{23} & -L_3 S_1 S_{23} & L_3 C_{23}
\end{bmatrix}
\begin{bmatrix}
f_x \\
f_y \\
f_z
\end{bmatrix}
\quad (16)
\]
5 Control System

The control system on which the interface is based is shown in the control Diagram below. The different control blocks, system variables and state transitions are explained throughout the paragraphs.

5.1 Control Diagram

The robot is constantly controlled with a proportional controller (P-controller). It controls the motion and the position of the of the manipulator’s end-effector. In the diagram, the control scheme of the complete system is shown (Fig. 5-1). The real joint angle signal ($\theta_{\text{real}}$) is the negative feedback from the robot. It is subtracted from the reference joint angles ($\theta_{\text{ref}}$), which gives the angle error ($\Delta\theta$). This error is the input for the P controller to control the error to zero. The state-flow (SF) block observes the angle error, the joint currents ($i$) and the reference angles. This block is the switching mechanism of the system and switches the system between moving and stationary state. The human intention (HI) block detects disturbances caused by human intent ($d_{\text{HI}}$) in the current signal. This block runs in the stationary state of the system and it updates the joint angles after HI is detected. This switches the state of the system back to motion state.

![Fig. 5-1: System control scheme](image-url)
5.1.1 Proportional controller

The state variable of the system is $\theta$ and the proportional controller is used to control the robot’s actuator joint angle errors to zero. This makes the manipulator and its end-effector position controlled. The angle error is schematically shown in figure 5-2, where the difference between the reference angle $\theta_{\text{ref}}$ and the real angle $\theta_{\text{real}}$ is drawn resulting in the angle error ($\theta_{\text{error}}$).

![Fig. 5-2: Angle error](image)

The proportional control law of the system is:

$$u = K_p(\theta_{\text{ref}} - \theta_{\text{real}}) = K_p \Delta \theta$$

This controller produces an actuator signal ($u$) that is proportional to the error signal ($\Delta \theta$). The system schematic (Fig. 5-4) of a single dc motor looks as follows:

![Fig. 5-3: Schematic P controller](image)
The error is amplified with a gain $K_p$ and goes into a saturation filter to make sure that the input signal of the motor is in the proper range of the dc motor. For the Edro dc motors this is between -5V and +5V.

The model DC motor is typically described by the differential equation below:\(^2\):

$$\ddot{\theta} + (\lambda)\dot{\theta} = \tau_{em} + \tau_{app} = \frac{K_i}{R} u + \tau_{app}$$

Where

$\ddot{\theta}$ = angular acceleration  
$\dot{\theta}$ = rotational angular velocity  
$J$ = moment of inertia  
$\lambda$ = coefficient of friction  
$\tau_{em}$ = electromagnetic torque  
$\tau_{app}$ = externally applied mechanical torque.

In case of the static torque measurement, the angular acceleration and velocity are zero. This implies the relation between the generated motor torque in the external applied torque given in § 3.4.2.

### 5.1.2 SF block

The state flow block switches the state of the system from stationary to motion state and back (Fig. 5-4). During motion state ([0]) the motion of the robot is controlled to a desired reference position. The robot has reached position, if the real angles are equal to the given reference angles. The angle error ($\Delta\theta$), the block’s input, becomes smaller than a certain threshold value $\varepsilon$ that is almost zero. In this case the system state is changed to stationary ([1]).
In this state the robot is position controlled to this reference position with the P-controller. The block has two outputs. One is the feed through of the observed current \(i\) and the second is the trigger signal \(\{1,0\}\). In case of 1, the HI block is remains unchanged. \(\theta_{\text{ref}}\) is set to this value and waits for the inputted \(\theta_{\text{ref}}\) to become different. At the moment the reference angles of the system are updated by the HI block, it changes \(\theta_{\text{ref}}\) to the new reference angle values \(\theta_{\text{ref}}(\text{new})\) and the inequality in the SF block, \(\theta_{\text{ref}} \neq \theta_{\text{ref}}\), counts. Then the state of the system is switched to state (0) again and the feed through of \(i\) is stopped.

The following switching table describes the switching points of the system. The red shaded blocks indicate the switching triggers.

<table>
<thead>
<tr>
<th>Step</th>
<th>input</th>
<th>Step description</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta_{\text{ref}})</td>
<td>(\Delta \theta)</td>
<td>(\theta_{\text{ref}} \neq \theta_{\text{ref}})</td>
<td>({1,0})</td>
</tr>
<tr>
<td>1</td>
<td>(\theta_{\text{ref}})</td>
<td>&gt; (\varepsilon)</td>
<td>Controlling the angle error to 0</td>
</tr>
<tr>
<td>2</td>
<td>(\theta_{\text{ref}})</td>
<td>&lt; (\varepsilon)</td>
<td>i observed by HI block</td>
</tr>
<tr>
<td>3</td>
<td>(\theta_{\text{ref}})</td>
<td>&gt; (\varepsilon)</td>
<td>HI impulse occurs</td>
</tr>
<tr>
<td>4</td>
<td>(\theta_{\text{ref}})</td>
<td>&lt; (\varepsilon)</td>
<td>HI impulse detected</td>
</tr>
<tr>
<td>5</td>
<td>(\theta_{\text{ref}}(\text{new}))</td>
<td>&gt; (\varepsilon)</td>
<td>A new reference angle</td>
</tr>
</tbody>
</table>

Tab. 5-1: Switching table of the SF block
5.1.3 HI block

In stationary state, the HI block observes and detects the human intentional force applied to the Edro (Fig. 5-5). At trigger signal 1 from the SF block it starts observing the input current ($i$) for current fluctuations ($\Delta i$). A fluctuation of the current that exceeds a certain threshold value is recognized and detected as HI. This threshold value defines the lower bound of the HI region ($R_{HI}$). If a disturbance fluctuation is detected $F_{HI}$ is estimated from the measurement. The new reference joint angle ($\theta_{ref}$) values are determined and updated as output of the block. At trigger signal 0 the block maintains $\theta_{ref}$ constant to these updated values.

In this model the robot is statically balanced and interaction takes place while the robot is in static equilibrium, therefore there are no other factors influencing the joint current fluctuations than human interaction. Every external impact can be recognized as a human impact. In the case the robot would not be balanced than the dc motors compensate the weight of the robot. Then the current draw through the motor will increase to a higher constant level. This does not affect the current fluctuation. The motors also have certain amount of static friction. In Phri, the human’s force first has to create a torque that crosses this friction before the
manipulator is affected by it. In this model human intention is only sensed in case the friction is crossed and therefore it does not influence the measurement.
6 Interface

The Phri interface is a software model that deals with the control software of the robot and the communication between the robot and its human controller. The interface model is built in a Matlab/ Simulink software environment, where the system analysis and the system control is integrated in one model. Depending on the system state the interface controls the motion or the position of the manipulator. In the stationary position control state the model observes the physical interaction and detects human intent applied on the robot. It translates the obtained information into the next coordinate and updates the manipulator’s end-point position. Eventually the model is implemented in a real setup and an application is made in which the robot is used to pick and place an item (Ch. 7).

6.1 Simulink / Matlab Model

Prior to the activation of the interface, the system is initialized. The start function runs the interface model enables physical interaction with the Edro.

Edro_Initilise_global_variables

Initialisation calibrates all the global variables to the initial settings. The robot initializes at home position, with initial end-point P coordinate \((x,y,z) : (0.25, 0, 0.25)\). It turns the initial joint angles to a rotation of 0 radians.

Edro_Start_Interaction_Interface

The interaction Interface is the control function of the two simulink models and switches between the two system states. It switches the setup, from position control state, in which HI is observed and detected, to the position update state, in which the robot is motion controlled to the next desired position.
6.1.1 Position update model

The position update Simulink model represents the system’s motion state (Fig. 6-1). It contains the position update, the inverse kinematics, the motion control and the pick and place application features (Position Check, Gripper). It is integrated in a sequence of subsequent Matlab functions.

```
Position Update
```

This function flow is assigned to system state [0]. The description of the separate control algorithms are explained below, see the appendix for the corresponding Matlab files.

**Edro_Position_Update**

Position update determines the next desired reference position based on the estimated human intentional force. A force results in a motion in the direction of the vector. A force magnitude of ten Newton results in a five centimetres displacement.
Edro_Inverse_Kinematics

The updated position coordinate is translated into joint angles by the use of inverse kinematics (Ch. 4.1.1). The robot joint angle vector \([\theta_1, \theta_2, \theta_3]\) is updated.

Edro_Position_Check

The position check is an application feature and verifies, based on the end-effector’s updated z coordinate and base angle, whether the end-point of the robot enters a pick or place region in the workspace (Ch. 7). If so, the robot joint angle vector is updated again to respectively a pick or place position of the end-point.

Edro_Motion_Control

The motion is controlled with a P controller that controls the movement of the Edro to the next position. Each joint is actuated, given a new set of joint angles belonging to the updated end-point coordinate. When the joint angle error is zero, the system is switched to stationary state [1].

Edro_Gripper

The Edro_Gripper function is also a feature that belongs to the application. The position is checked for being at a pick or place coordinate. If so, the pick or place action of the gripper is executed. If the application is implemented in the interface, stationary state will run after this function.

6.1.2 Human Intention Detection model

The human intention detection model represents the stationary state of the system and is the operation framework for the position control of the Edro (Fig. 6-2). The interface observes and detects human intention. The joint torques are observed via the data acquisition and signal processing until HI detection occurs.
The data is acquired with the Simulink data acquisition toolbox application, the analog input block. It inputs the data at a sample rate of 0.01 second. The signal parameters are set to 500 samples per second with a block size of 5.

The Matlab functions concerning this model representing the system state [1] are Position Control, Data Logging and HI.

Edro_Position_Control

With a sample rate of 0.01 the robot arm is position controlled through the proportional control law of the system to maintain its position.

Edro_Data_Logging

Every 0.01 second the joint torque vector \([bm, sm, em]\) data is logged in matrix in the matlab global variable database.
The HI function runs within the if-function of the model. The signal processing puts through only the detected HI signals to this block. The detection activates the HI function and it determines the maximum current fluctuations from the measurement. These current values are used to estimate the joint torques for determination of the human intentional force. If during observation HI is detected, the system is switched back to motion state [0] to start the position update of the system again.

6.1.3 Signal processing and HI detection

The observed analog input current signal from the DAQ system is processed to detect human intentional interference. The signal processing part of the model detects HI and triggers the switch back to motion state. As soon as HI is detected the system will activate the motion state. A typical input signal in which detection took place is shown below. The signal processing step in the model detects the human impulse to the robot.

![Current sensing plot](image)

**Fig. 6-3: Typical HI detection**
At detection $F_{HI}$ is estimated and following to that the new reference position is determined. The system switches back to motion state to bring the robot in the new desired position.

The signal processing is explained according to the foregoing HI detection plot. The Simulink scope below represents the same signals and shows the observation of the incoming sensor data. The first step is the projection of the input signals to the zero line, done by a dead zone block (Fig. 6-4: Input signal projection to zero). From then all signals are set at zero value.

Then the absolute value of the signal is taken and a rate transition is done to pass it through a first order Butterworth filter (Fig. 6-2). This action deletes the noise from the signals. Then the input signals are separated, so they can be observed for HI impact independently. The Simulink scope images of the separate filtered signals are shown in figure 6-5. They represent again the same input sensor signals as before.
Another dead zone operation is done on the filtered signals in which the threshold value for HI detection is set to 0.1 (Fig. 6-6). The zero is then placed on the dead zone threshold value (DZv). A current fluctuation signal is recognized as HI if it first exceeds the DZv and then crosses the line from above, with a Simulink zero crossing block. This indicates that HI is detected and the if-block is triggered that activates the system switch. It can be seen that in this measurement the shoulder signal indicates the HI detection as this signal crosses the DZv of 0.1 from above first (Fig. 6-6).
7 Application

A pick and place application is integrated in the interface to demonstrate it on a real system. The robot is directed to a certain position following a trajectory initiated by human pushes. The human can freely move the robot through the workspace towards a pick or place region until it reaches there. Pick and place areas are defined in the workspace of the robot arm shown in fig 7.1 and 7.2.

![Diagram of pick and place regions](image-url)

**Fig. 7-1:** Top view, x-y plane pick & place regions

**Fig. 7-2:** Side view of pick & place regions
The area boundaries are defined in the position check matlab file in the appendix. If P is within a bleu or a yellow region and its z coordinate goes below the z threshold value (0.16 m) entering the green area then the Edro performs a pick or place operation. The Edro goes to a specified coordinate corresponding to the action and according to that it grabs or releases an object.

The table ( ) shows a test run where the estimated $F_{HI}$ force components [$FP_x, FP_y, FP_z$] the updated joint angles [$\theta_1, \theta_2, \theta_3, a_1, a_2, a_3$] and position coordinate [$x, y, z$] are shown. The first column, step 1, shows the initial state of the robot. The measured impulse applied to the robot instigates the estimation of the corresponding $F_{HI}$ components (Fig. 7-3). This force estimation leads to the first position and angle update of the manipulator shown in step of the table.

![Current sensing plot](image)

**Fig. 7-3: Current measurement of 1st impulse**

Now, the end-point of the robot is not within any pick or place region yet. The second position update in step 3 it enters the x-y plane pick region ( $a < -710$). In
the fourth update the end-effector also enters the pick & place region of the x-z plane (z < 0.16m), which causes the pick operation to execute. The robot moves to the accompanying robot joint angles (a1, a2, a3) which are (-714, -582, -668).

<table>
<thead>
<tr>
<th>Step</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Pick</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPx [N]</td>
<td>0</td>
<td>-18.794</td>
<td>-13.121</td>
<td>1.918</td>
<td>8.121</td>
<td></td>
</tr>
<tr>
<td>FPy [N]</td>
<td>0</td>
<td>-10.422</td>
<td>-18.535</td>
<td>-15.900</td>
<td>2.262</td>
<td></td>
</tr>
<tr>
<td>FPz [N]</td>
<td>0</td>
<td>-7.624</td>
<td>0.619</td>
<td>-1.308</td>
<td>-16.124</td>
<td></td>
</tr>
<tr>
<td>θ1 [rad]</td>
<td>0</td>
<td>0.322</td>
<td>1.013</td>
<td>1.151</td>
<td>0.987</td>
<td></td>
</tr>
<tr>
<td>θ2 [rad]</td>
<td>0</td>
<td>-0.344</td>
<td>-0.319</td>
<td>-0.004</td>
<td>0.143</td>
<td></td>
</tr>
<tr>
<td>θ3 [rad]</td>
<td>0</td>
<td>0.438</td>
<td>0.408</td>
<td>0.171</td>
<td>0.356</td>
<td></td>
</tr>
<tr>
<td>a1</td>
<td>-492</td>
<td>-569</td>
<td>735</td>
<td>-768</td>
<td>-768</td>
<td>714</td>
</tr>
<tr>
<td>a2</td>
<td>-484</td>
<td>-401</td>
<td>-408</td>
<td>-483</td>
<td>-582</td>
<td>582</td>
</tr>
<tr>
<td>a3</td>
<td>-563</td>
<td>-721</td>
<td>-710</td>
<td>-624</td>
<td>-668</td>
<td>668</td>
</tr>
<tr>
<td>x [m]</td>
<td>0.250</td>
<td>0.156</td>
<td>0.090</td>
<td>0.100</td>
<td>0.175</td>
<td>0.1748</td>
</tr>
<tr>
<td>y [m]</td>
<td>0.000</td>
<td>0.052</td>
<td>0.145</td>
<td>0.224</td>
<td>0.232</td>
<td>0.2320</td>
</tr>
<tr>
<td>z [m]</td>
<td>0.250</td>
<td>0.212</td>
<td>0.215</td>
<td>0.208</td>
<td>0.128</td>
<td>0.0680</td>
</tr>
</tbody>
</table>

Tab. 7-1: Application test run

Then the Gripper Matlab function recognizes this position and grabs the object. From this point the robot can be brought in the same way to a place area.
8 Conclusion

In this research a new approach for physical human robot interaction without force sensor is proposed. The first step is made towards flexible human assist robot systems that cooperate with the human and communicates on physical level. A Phri interface is developed for a 3 DOF position controlled statically balanced planar robot arm. The physical interaction takes place in the stationary state of the system where the human intentional force applied to the robot is estimated by the system.

The three dimensional force measurement is achieved by applying a cheap eddy current sensing technique. It measures the current fluctuations in the joints. The joint torques are estimated by the linearly proportional relation between dc motor current and torque. The manipulator Jacobian translates the joint torques to the human intentional end-point force $F_{HI}$. This technique decreases the number of expensive strain gauge force sensors used in conventional physical interactive robot systems. It also enables the human to physically interact with the robot at any point on the robot. In this way the interaction itself becomes more flexible.

The interface updates the robot’s end-effector position by adapting to human intention through following the direction and the magnitude of human exerted force on the manipulator. In the control of the system a switching mechanism is developed that updates the system based on human intention. It switches between stationary state and motion state. In stationary state human intention is observed and detected. In the motion state the robot updates the position.

Although the first step has been made in measuring human intention, still a lot of further developments in the HARDIS research are necessary. The next step is to observe, detect and react to human intention while in motion and adjusts and adapt dynamically to the measurements. The model needs to be extended with the dynamical behaviour of the manipulator to get a complete description of the system. Link inertias, masses, centrifugal and gravity terms come into play then as well as the actuator dynamical behaviour as motor friction.
A second step to make is to add load and an additional load measurement to the system. This results in extra force influences on the system. It necessitates a force sensing technique that can distinguish forces acting on the system generated by the manipulated load from human intentional forces applied to the system by the human. Signal analysis will become an important factor for the recognition of the source of a sensed force.
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Appendix