Department of Precision and Microsystems Engineering

Integration of a Needle Haptic Telemanipulation System

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It is an interesting adventure to explore the field of mechatronic, especially the haptic technology field. This thesis gives me a great opportunity to apply theory into practical, even through the process is not that smooth. Also it is a lot fun of studying different components and combining them as a complete system yourself. When you get the feeling of remote environment at master side, the experience is amazing.

I learnt a lot of things from this project, which are not only the specific knowledge related to mechatronics but also the doing thing methods. I know what I learnt during this one year project is just “the tip of iceberg” in huge mechatronic world. A journey of engineering world is just beginning.

Sa Wang
Delft, October 2016
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# Contents

1 Introduction .......................... 1
   1.1 Background ................................. 1
   1.2 Task description ......................... 2
   1.3 Requirement ............................... 2
   1.4 Thesis review .............................. 2

2 Literature Review ...................... 3
   2.1 Steerable needle review .................... 3
      2.1.1 Bevel tip needle ...................... 3
      2.1.2 Steerable needle of MISIT lab .......... 3
   2.2 Haptic teleoperation system review .... 4
      2.2.1 Concept introduction and application .... 4
      2.2.2 Development history ................. 4
      2.2.3 Modeling methods .................... 5
      2.2.4 Control architecture ............... 5
   2.3 State of the art ........................... 6

3 System Integration .................... 7
   3.1 System overview .......................... 7
   3.2 Components description .................. 7
      3.2.1 Slave part ............................ 7
      3.2.2 Controller ............................ 8
      3.2.3 Master device .......................... 9
   3.3 Detailed schematic of connected system .... 10

4 Controller Design ..................... 11
   4.1 Model Identification ..................... 11
      4.1.1 The working principle of slave device .... 11
      4.1.2 Frictional force and gravity force identification ... 12
      4.1.3 Open loop model identification .......... 13
      4.1.4 Close loop identification ............. 14
   4.2 Unilateral Controller Design ............. 15
      4.2.1 Control system overview ............. 15
      4.2.2 Controller model ........................ 15
      4.2.3 Close loop response ................... 16
      4.2.4 Pre-filter design .................... 17
   4.3 Bilateral Controller Design .............. 18
      4.3.1 Control architecture .................. 18
      4.3.2 Proposed gain scheduling position controller design .... 19
      4.3.3 Needle insertion with integrated haptic teleoperation system .... 20
      4.3.4 Proposed Interaction Regulator Design ....... 21

5 Performance Evaluation ............... 27
   5.1 Position repeatability of system in free air environment .... 27
   5.2 Dynamic range of system ................ 27
   5.3 Stability .................................. 28
      5.3.1 Definition of stability ............ 28
      5.3.2 Stability analysis .................. 29
### Conclusion and Recommendation

6.1 Conclusion .......................................................... 31
6.2 Recommendations .................................................. 32
   6.2.1 Recommendations considering slave part ................. 32
   6.2.2 Recommendations considering master part ............... 32
   6.2.3 Recommendation considering control architecture .......... 32

### Bibliography

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bibliography</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Detailed wire connection</td>
</tr>
<tr>
<td>A.1</td>
<td>The schematic of wire connection .......... 37</td>
</tr>
<tr>
<td>A.1.1</td>
<td>Wire connection of slave ................. 37</td>
</tr>
<tr>
<td>A.1.2</td>
<td>Wire connection of master ............... 37</td>
</tr>
<tr>
<td>B</td>
<td>Force sensor test</td>
</tr>
<tr>
<td>C</td>
<td>Filter Design</td>
</tr>
<tr>
<td>C.1</td>
<td>Noisy signal analysis ......................... 41</td>
</tr>
<tr>
<td>C.2</td>
<td>Filter Design ......................................... 41</td>
</tr>
<tr>
<td>C.2.1</td>
<td>Frequency Response of Filter .................. 41</td>
</tr>
<tr>
<td>C.2.2</td>
<td>Performance measurement ...................... 42</td>
</tr>
<tr>
<td>D</td>
<td>Simulink Block Diagram of Controller</td>
</tr>
<tr>
<td>D.1</td>
<td>Whole block diagram ................................ 44</td>
</tr>
<tr>
<td>D.2</td>
<td>Master part ............................................. 45</td>
</tr>
<tr>
<td>D.3</td>
<td>Control part .......................................... 45</td>
</tr>
<tr>
<td>D.4</td>
<td>Security part .......................................... 46</td>
</tr>
<tr>
<td>D.5</td>
<td>Slave part .............................................. 46</td>
</tr>
<tr>
<td>E</td>
<td>Data Sheet</td>
</tr>
<tr>
<td>E.1</td>
<td>Encoder (slave part) ......................... 48</td>
</tr>
<tr>
<td>E.2</td>
<td>Encoder (master part) ....................... 49</td>
</tr>
<tr>
<td>E.3</td>
<td>Actuator (slave part) ....................... 50</td>
</tr>
<tr>
<td>E.4</td>
<td>Actuator (master part) ....................... 51</td>
</tr>
<tr>
<td>E.5</td>
<td>Amplifier (slave part) ....................... 52</td>
</tr>
<tr>
<td>E.6</td>
<td>Amplifier (master part) ....................... 53</td>
</tr>
<tr>
<td>E.7</td>
<td>Bachmann Controller (Digital interfaces) .... 54</td>
</tr>
<tr>
<td>E.8</td>
<td>Bachmann Controller (Digital interfaces) .... 55</td>
</tr>
<tr>
<td>E.9</td>
<td>Bachmann Controller (Analog interfaces) .... 56</td>
</tr>
<tr>
<td>E.10</td>
<td>Bachmann Controller (Analog interfaces) ..... 57</td>
</tr>
<tr>
<td>E.11</td>
<td>Bachmann Controller (Encoder interfaces) .... 58</td>
</tr>
<tr>
<td>E.12</td>
<td>Bachmann Controller (Encoder interfaces) .... 59</td>
</tr>
<tr>
<td>E.13</td>
<td>Linear stage ......................................... 60</td>
</tr>
<tr>
<td>E.14</td>
<td>Force sensor ........................................... 62</td>
</tr>
<tr>
<td>F</td>
<td>List of Matlab code</td>
</tr>
<tr>
<td>F.1</td>
<td>Forward Kinematics of Manipulator .......... 63</td>
</tr>
<tr>
<td>F.2</td>
<td>Motor torque calculation of manipulator ..... 70</td>
</tr>
<tr>
<td>G</td>
<td>Derivation of elements inside H matrix</td>
</tr>
<tr>
<td>G.1</td>
<td>Control architecture without interaction regulator .......... 71</td>
</tr>
<tr>
<td>G.2</td>
<td>Control architecture with interaction regulator .......... 72</td>
</tr>
<tr>
<td>G.3</td>
<td>Identification of master device ............... 72</td>
</tr>
</tbody>
</table>
Introduction

1.1. Background

Percutaneous needle insertion is frequently used in medical procedures for diagnosis and treatment. Needles need to reach specific locations in human body without damaging organs around. Accurately driving needle towards desired point is challenging for clinicians due to the unpredictability of needle motion. Hence, a steerable needle with controller may decrease the difficulty of this procedure and increase the position accuracy. The MISIT Lab of TU Delft has developed a new kind of steerable needle (Fig 1.1).

![Actuated tip of steerable needle](image1)

![Steerable needle](image2)

Figure 1.1: The tendon-driven needle consists of a stylet with radius $r_1$ and grooves for optical fibers ($f$), and a cannula with radius $r_2$ and grooves for the actuation cables ($c$). Steering is realized by the four actuators located at base.

The novelty of this needle is that it allows the orientation of needle tip to be steered by four tendons instead of spinning the needle along longitudinal axis, to reduce additional damage to tissue. By changing the orientation of the actuated-tip, the steering direction of needle and amount of deflection can be controlled. To reach the desired target in soft tissue, the needle is design to work with 3 DoF: rotation in $x$, $y$ directions and translation in $z$ direction.

To help operator manipulate this kind of needle accurately and safely, a haptic tele-operation system needs to be integrated. The haptic tele-operation system helps operator perform a task in remote environment and gives operator force feedback from environment. As shown in figure 1.2, haptic teleoperation system generally consists of master device, controller and slave device. In this project, the needle plays slave device role in this system. Moreover, a parallel manipulator is provided by haptic lab of TU Delft to take over the job of master device in the haptic telepereation system.

The main advantage of using this kind of manipulator with parallel structure is that it allows all actuators assembled on the base (see Fig 1.3), which makes the inertia of moving part reduced compared with using serial robot. The force feedback from environment is provided by the actuator on the base and delivered with
1. Introduction

Figure 1.2: Schematic of haptic teleoperation system. M = master device, S = Slave device, C = controller

light bar linkages. Due to the low inertia of master interface, the force sensitivity that operator can feel is improved.

Figure 1.3: Parallel manipulator of haptic lab made by Teun

This thesis aims to create a interface between operator and steerable needle with existing parallel manipulator. Based on the background information mentioned above, the task of this thesis would be depicted in following section.

1.2. Task description

The task of this thesis is to integrate a haptic teleoperation system for needle insertion with existing available devices and design a bilateral controller for this system. As the most challenging part is using force measured from z direction to give feeling to operator, a 1 DoF needle is used instead of 3 DoF steerable needle to investigate the application of haptic teleoperation system in needle insertion process.

1.3. Requirement

The requirement for this mechatronic system based on the motivation of this thesis is listed as follow:

- Operator can implement a needle insertion action with this system.
- Operator can feel both counter force and the stiffness varying during needle insertion process.
- The system can be implemented safely.

1.4. Thesis review

This thesis describes how a haptic teleoperation system for needle insertion is integrated step by step and how a bilateral controller is designed. In chapter 2, a review of literatures regarding to steerable needle field and haptic control field is depicted. Chapter 3 describes the system integration process. The available components are introduced first, an architecture is presented in this chapter secondly and finally a practical wire connection is depicted. The controller design part is placed in chapter 4 where a bilateral controller is designed step by step. The evaluation of system performance is discussed in chapter 5. In chapter 6, conclusions are listed and remarks based on this thesis are proposed. Multiple appendices on different subject are also present.
Literature Review

After drawing the background and task of this thesis in chapter 1, a literature review is summarized in this chapter to support the research of this thesis. The literature review will first start to introduce the research background of steerable needle which describes development of steerable needle. Secondly, the research field of haptic teleoperation system is presented by following time order. Various types of control architecture in haptic teleoperation system are presented and discussed. The control architectures used in this thesis will be depicted in chapter 4.

2.1. Steerable needle review

2.1.1. Bevel tip needle

Various researchers have been implementing in developing a steerable needle which can reach the specific location in human body with certain accuracy. Many studies concentrate on steering needle with bevel tip (see fig 2.1). The rotation of bevel tip needle along its longitudinal axis can steer a the needle in desired direction. The path can pre-defined by duty cycled spinning of the needle. [10],[5]

![Figure 2.1: The schematics of bevel tip needle](image)

2.1.2. Steerable needle of MISIT lab

However, spinning of the needle may result in additional damage to tissue which is not expected. Hence, steerable needles in soft tissue with smart mechanism design are presented recently. In MISTI lab of TU Delft, a novel method of steering needle (see fig 2.2) is developed based on a new needle design with an actuated-tip. The tip with conical shape is mounted on a ball-joint. The ball-joint is actuated by four tendons so that the ball can rotate in two DoFs, which allows tip to change orientation. With one translational actuation, the steerable needle can go through soft issue without spinning along longitudinal axis. [15]

To make the steerable needle reach required specific location in soft tissue, a robotic system with feed-back is also developed. The basic ideal of controller design is using both measured tip position and online estimated parameters as feedback to make the needle tip reach target position.(see fig 2.3) [16]

Additionally, the kinematics of needle is also investigated. Based on the difference of needle tip pose, the front frame offset can be estimated. The experiment result of this control method shows mean target errors of 1.33mm and 1.22mm in x and y- direction respectively. This result is collected when no obstacle is taken into experimental environment.[16]
2. Literature Review

2.2. Haptic teleoperation system review

2.2.1. Concept introduction and application

Haptic teleoperation system is a tool-based interaction system where the tool is divided into two parts (master device and slave device) connected with controller. Teleoperation is to use a remotely controlled robotic tool to perform a task in remote environment. When interaction force from slave side communicated to operator via master device, this system can be called a "haptic teleoperation system" [2]. Haptic teleoperation technology is widely used in hazardous manipulation [3], deep-sea robotics and space operation. Also, "drive-by-wire system" for vehicle is a kind of haptic teleoperation system [11].

2.2.2. Development history

Since 1950 in the US, the earliest remote-controlled robotic tool has already been developed at the Argonne National Laboratory, to manipulate radioactive objects. The exploration on better performance of haptic system has never stopped.

In the 1970’s and 1980’s, teleoperators starts to be used for orbital system. The basis for modern teleoperation is first built by Ken Salisbury, Blake Hannaford, Antal Bejczy and Paolo Fiorini. The teleoperator is modeled as linear network systems, which increased accuracy of performance prediction [7].

In 1990’s, computer simulation and virtual reality started to appear in teleoperator research. It made it possible to interact with a simulated object using haptic device. Both slave robot and environment can be simulated in virtual environment. Therefore, haptic devices are widely used in computer games, certain virtual reality CAD tasks and surgical training program [13].

In the 2000’s, teleoperation stepped into the surgery theater. There are various surgical operation task using haptic feedback to improve patient safety and to reduce surgeon’s workload [14].

Currently, an increased interest of this field appeared in human operator perception and haptic communication channel. The traditional teleoperator development was strongly linked to industrial robot research, where high bandwidth and position accuracy are the main purpose of control [2]. However, human perception is limited in many ways e.g. the judgement of size by fingers [6].
2.2.3. Modeling methods
To analysis the stability and performance of haptic teleoperation system, every segment of teleoperator would be modelled. The communication signals are so called “power variables” effort (force) and flow (velocity)[4]. This leads to a definition of impedance which means a force over velocity in frequency domain. Some researchers also define the impedance as force over position[9]. In this thesis, impedance of force over velocity is confirmed. The teleoperator model normally contains four parts: operator model, master model, controller model and slave model. Each component is modelled separately, and then combined into one complete teleoperation(fig 2.4) model using the H-matrix notation[7].

![Figure 2.4: The schematics of complete haptic teleoperation system.](image)

V<sub>e</sub> is the velocity of slave robot, F<sub>e</sub> is the interaction force between slave robot and environment, V<sub>h</sub> is the velocity of master device and F<sub>h</sub> is the interaction force between master interface and human hand. F<sub>mc</sub> and F<sub>sc</sub> are the forces generated by controller, going to master and slave separately.

In Hannaford’s paper[7], the most popular representation of Connected Teleoperation System(CTS) is introduced and named as Hybrid Matrix configuration(fig 2.5). In this hybrid matrix model, master velocity (V<sub>h</sub>) and slave force(F<sub>e</sub>) are chosen as inputs, slave velocity(V<sub>e</sub>) and haptic force(F<sub>h</sub>) are regarded as outputs.

![Figure 2.5: The Hybrid Matrix Model](image)

The elements h<sub>ij</sub> in H-matrix (2.1) are rational transfer function which contains all the information of device models and controller.

\[
\begin{bmatrix}
F_h \\
-V_e
\end{bmatrix} =
\begin{bmatrix}
h_{11} & h_{12} \\
h_{21} & h_{22}
\end{bmatrix}
\times
\begin{bmatrix}
V_h \\
F_e
\end{bmatrix}
\]

(2.1)

The H-matrix components h<sub>ij</sub> can be interpreted as[7]:

\[
H = \begin{bmatrix}
\text{input impedance} & \text{force scale} \\
-\text{velocity} & \text{output admittance}
\end{bmatrix}
\]

(2.2)

2.2.4. Control architecture
Numerous control architectures are proposed for haptic teleoperation through the years. This section gives an overview of the most popular control architectures used in haptic field.

**Position Error Control**
The first control architecture documented is the Position Error Control, (also called position-position control, position-exchange control and bilateral position control)[9]. The idea of this controller is that the position difference between two devices is measured, and the controller makes the position error as same as possible. The layout of control structure (fig 2.6a) is drawn in the style of Lawrence and Salcuddean[12][17].

**Position-Force Control**
(a) The schematic of position error control. The position error is fed back with gain $K_p$ to both master and slave. ($F_h^*$ and $F_e^*$ are active forces from operator and environment)  
(b) The schematic of position force control. $K_f$ is the force feedback gain. The force is presented subsequently to operator via master.  
(c) Four channel control architecture. The eight gain blocks ($C_1$ to $C_6$, plus $C_m$ and $C_s$) are independent in respect to each other

Figure 2.6: Overview of three kinds of control architecture

This control strategy is that operator give commands to slave device, and slave measured force which is presented to operator by master device[8]. A schematic of controller is presented in fig 2.6b as follow.

**4-Channel Control**

The 4-channel control method (fig 2.6c) proposed by Lawrence [12] is a milestone in development of haptic field. This method shows the advantages of communicating both forces and positions between master and slave. This control architecture is further improved by Salcudean, Hashtrudi-Zaad and Zhu to further improve stability/performance trade-off based on local force-feedback [18].

The idea of this 4-channel control method is to optimize the eight parameters based on performance function. Lawrence also discussed how to adapt the scheme to compensate for communication time delay [12].

### 2.3. State of the art

The interdisciplinary cooperation in engineering circle has become closer and closer. Since 2000, teleoperation has taken step into surgery theater. At that time, there was only visual feedback, and no haptic feedback, which means that doctors had no feeling of what they are doing. Recent years, haptic feedback is often suggested to help improve operation performance and patient safety [14]. But how good the haptic feedback can help is still under investigation. Also, in TU Delft, how much can needle manipulation benefit from haptic feedback is a valuable issue for MISIT lab [1].

This thesis aims to make a contribution in application of haptic teleoperation in clinical technology to study how good haptic feedback can improve needle insertion performance.
In the previous chapter, literatures of steerable needle and haptic teleoperation system are reviewed. To investigate the application of haptic teleoperation system in needle insertion, each component should be integrated as a connected system.

In this chapter, a overview of haptic teleoperation system is depicted first. Secondly, the components (actuators, sensors and real-time controller) involved would be introduced and testified separately. Finally, a more detailed schematic of connected system will be demonstrated.

### 3.1. System overview

Generally, a haptic teleoperation system contains three main subsystems: a master device, a slave device and a controller used for interactive communication between master and slave. A typical architecture of a haptic teleoperation system is shown in Fig.3.1.

![Figure 3.1: A haptic teleoperation system](image)

It can be seen from Fig.3.1 that there are two flows: one delivers operator motion information from master to slave via controller, the other one transfers interaction force from slave to master via controller as well. The functionality of master part is to create an interface between controller and operator so that motion of human can be measured and interaction force can be generated as well. As for controller part, all measured data are collected and the control signals are computed here. Correspondingly, the job of slave is to follow the commend from control and to provide force data back to controller simultaneously.

### 3.2. Components description

This section will introduce the components (actuators, sensors and real-time controllers) inside slave, controller and master.

#### 3.2.1. Slave part

In this thesis, a needle mounted linear stage, EC Motor with an encoder and a force sensor constitute the slave part. The configuration of slave robot is described in Fig.3.2. The components inside slave part will be described and discussed separately in the following section.

**Linear stage**

The linear stage in this thesis is a ball screw stage with 5mm per revolution. The total travel length can be up to 400mm with accuracy of ±12µm. Two sensors are mounted on the top and bottom of spindle to guarantee the safety of linear stage. When the platform reaches the end of spindle, the output of sensors will
3. System Integration

(a) Inside view of slave part  
(b) Outside view of slave part

Figure 3.2: The configuration of slave robot. The left figure shows what is side the slave robot and right figure shows the outside view of slave robot. In slave part, the linear stage provided a vertical moving platform where both force sensor and needle are mounted. The platform is actuated by a spindle inside which is rigidly connected with a EC motor and encoder. The top and bottom limit sensor will give a positive signal when the platform reach the end of both sides.

change from 0 to 1. Then the stage will be stopped anyway via controller. More details about linear stage are available in Appendix E.13.

**EC Motor and amplifier**

The EC motor is a three phase synchronized motor collaborating with an amplifier. By using amplifier, the motor current is controlled to be proportional to control voltage which is provided by controller. The motor time constant is 7.64ms, which means the bandwidth of motor can be 130.9 Hz. Compared with human hand motion (approximately 10Hz), the motor can be assumed to ideal. The more detailed characteristics of motor and specification of amplifier can be found in Appendix E.3 and E.5.

**Encoder**

The encoder in slave part is an incremental encoder with resolution of 7500 per revolution. It measures the position of spindle, by multiplying measured position with revolution of ball screw, the position of platform can be measured indirectly. Hence, the accuracy of measured result is not only related to the resolution of encoder but also related to how rigid the connection between spindle and platform is. During needle insert process, both speed and actuation force are relative low, therefore the connection between spindle and platform can be regarded as an ideal rigid connection. The detailed pin information and working condition about encoder are available in appendix E.1.

**Needle and force sensor**

To make the setup close to real clinical operation, the needle used in this experiment is choose to be a needle for bone marrow injection. The needle root is rigidly connected with a force sensor with maximum capacity of 5 lbs. The output signal of force sensor propagates with noise of approximate 40%, therefore a filter with cut off frequency of 30Hz is designed to filter out the noise. The detailed information about the filter and force sensor is presented in appendix E.14.

3.2.2. Controller

The controller part is taken over by a real time controller- "Bachmann Controller" (see Fig3.3) which can receive and send both digital and analog signal with sampling frequency of 1000Hz.

Bachmann controller contains five function module: Power supply, Processor Module, DIO Module, AIO Module and CNT Module. The power supply module provides a DC voltage of 24V for other modules. And the Processor Module takes over tasks of computation, databases and signal processing. The digital signals are
3.2. Components description

Received and send by DIO Module. The high input voltage range is from 15V to 34V and the low input voltage range is from 0 to 5V. Correspondingly, AIO Module creates interfaces for analog signal of ±10V. Additionally, the encoders signal can be received by CNT Module. The detailed information are available in appendix E.10, E.8 and E.12.

Inside the Bachmann controller, the control architecture can be programmed with SIMULINK in MATLAB and the control command can be given by operator via software(Solution Center) in PC. The details of control architecture will be explained in chapter 4.

3.2.3. Master device

The parallel manipulator (Fig.3.4) designed by Teun in haptic lab plays master part in haptic teleoperation system. Operator can manipulate needle by holding joy stick in the end with hand. The manipulator has 3 Degrees of Freedom (DoFs). In translational direction, the working range can be up to 20cm and maximal force of 10N can be generated by 4 DC Motors. Also, the manipulator can rotate from −20 deg to +20 deg with maximum torque of 0.3Nm. In this research, only translation is used (the black arrow in figure 3.4).

Figure 3.4: Parallel manipulator designed by haptic lab. It consists of 4 parallel limbs called lower legs, connected with a rotational joint to a rigid base and, on the other sides to another 4 bars called upper limbs. The 4 upper bars are connected together with a cross-shaped rigid body, thereby making it an over actuated 3-DoF manipulator.
Actuator
To simulate the interaction force from slave side, four DC motors with are mounted on root of low legs to generate required force. A cable transmission is used to transfer motor torque to lower limb. The transmission ratio is 1 to 7, which means the torque are magnified 7 times. Base on kinematics of manipulator (see appendix F), the required motor current can be calculated to provide feel to operator via interface.

Encoder
Four encoders with 4000 impulses per rotation are mounted with the four actuators separately to measure the rotation of lower limbs. Based on the kinematics of manipulator, the motion of operator hand motion can be estimated.

3.3. Detailed schematic of connected system
Based on the concept of haptic teleoperation system mentioned above, the components are connected and integrated with Bachman controller. The schematic of connected haptic teleoperation system for needle insertion is shown in figure 3.5.

![Figure 3.5: The schematic of connected haptic teleoperation system. The black solid lines mean the torque output from motor, the yellow solid lines mean the measured position of motor, the red lines are the analog output and input signals from Bachmann controller and blue lines represent the digital signal flow. The double black solid lines mean the rigid connection, while the double black lines with arrows represent interaction relation.](image)

The architecture of system demonstrates the clear relation of different devices. The Bachmann controller collects measured data from sensors and sends control signals to amplifiers. The mapping from collected signal and sending signal is determined by the control architecture inside Bachmann Controller which will be illustrated in next chapter.
Controller Design

In previous chapter, the system were successfully integrated with components available. And the schematic of system is depicted clearly with signal flow notations.

In this chapter, a whole controller design process will be described step by step. It will first start from identifying models in order to understand the property of system. Secondly, a unilateral needle position controller will be designed to make the stage follow motion of human hand measured from master device. Finally, a bilateral controller is designed to realize haptic teleoperation.

4.1. Model Identification

To design a controller for a system, a model identification process should be implemented to help designer understand the property of system. Based on the identified frequency response of system, the plant can be studied. In this thesis, slave robot model should be identified in order to design a controller making slave follow operator motion under certain bandwidth (around 7Hz).

4.1.1. The working principle of slave device

Before implementing model identification process, what is going on inside linear stage should be studied first. The working principle of linear stage it using a external ball crew return system to convert EC motor rotational motion into translational motion of stage. Figure 4.1 gives a demonstration of how a this type of ball crew system works.

As shown in figure 4.1, actuation mechanism of ball screw system is not a direct linear actuation method. The actual input is the torque from motor and the measured output from encoder is the revolution of spindle. Hence, the model identified is inertia of spindle and the environment around. Additionally, the utilization of ball crew system generates high frictional force because of the sliding between the threads of shaft and nut.

Figure 4.1: The working principle of external ball return system. The ball is returned to opposite end of the circuit through a ball return tube. The balls play a intermediate to transfer torque into force and convert rotation into translation.
4.1.2. Frictional force and gravity force identification

To get a insight of how much inside friction force is, a experiment is implemented to estimate the friction force. The idea is measuring the motor current when stage moves up and down with constant speed. The forces acting on stage in up and down situations are displayed in Fig. 4.2.

![Schematics of acting forces](image)

Figure 4.2: The configuration of frictional force measurement. The stage is actuated to move up and down with the same speed of 4mm/s.

When stage moves up with constant speed as show in figure 4.2a, total forces acting on stage should be zero according to newton second law. Therefore, the relation between them can be expressed as:

\[ F_{up}^a = M_g + F_f \]  \hspace{1cm} (4.1)

Similarly, when stage moves down with constant speed (see Fig. 4.2b), the relation between gravity, actuation force and friction force should be:

\[ F_{down}^a = F_f - M_g \]  \hspace{1cm} (4.2)

Hence, the gravity force and friction force can be represented by the two actuation forces as:

\[ F_f = \frac{F_{up}^a + F_{down}^a}{2} \]  \hspace{1cm} (4.3)

\[ M_g = \frac{F_{up}^a - F_{down}^a}{2} \]  \hspace{1cm} (4.4)

As the actuation force is provided by motor via ball screw system, the actuation forces is proportional to motor currents. The motor currents when stage moves up and down are displayed in Figure 4.3.

The motor currents in figure 4.3 show different value respect to local position of stage, however, the value difference between up and down situations is approximately constant value. This means that the friction force is various locally and the gravity force is constant.

Based on the relation between motor current and actuation force (105N/A), the value of gravity force can be calculated:

\[ M_g = \frac{F_{up}^a - F_{down}^a}{2} \approx 0.0675 A \times 105 N/A = 7.085 N \]  \hspace{1cm} (4.5)
4.1. Model Identification

As for friction force when stage moves with speed of 4mm/s, the range of friction force can be estimated:

\[ F_{f_{\text{max}}} = \frac{F_{\text{up}} + F_{\text{down}}}{2} \approx 0.3A \times 105\,\text{N/A} = 31.5\,\text{N} \]  
\[ F_{f_{\text{min}}} = \frac{F_{\text{up}} + F_{\text{down}}}{2} \approx 0.2A \times 105\,\text{N/A} = 21\,\text{N} \] (4.6) \hspace{1cm} (4.7)

In this section, slide friction force is identified when stage moves with constant speed of 4mm/s. The maximal friction force can be up to 31.5N and appears around 200mm, while the minimal friction force in range of 350mm-400mm is 21N. Moreover, the gravity force acting on the stage is estimated to be 7N.

4.1.3. Open loop model identification

The idea of open loop identification is giving a defined swept frequency input signal to target plant and measuring the corresponding output (see Fig 4.4). By analysing the relation between input and output in frequency domain, model property can be visualized in bode plot.

Because of the ball crew transmission inside, position of the stage is measured under the assumption that the backlash between stage and spindle is small enough. Moreover, the bandwidth of amplifier(1kHz) and the bandwidth of EC motor(130Hz) are much higher than the maximum frequency of input signal(10Hz). Hence, the amplifier and motor can be simplified to be ideal. Therefore, the open loop identification can reflect the system property under certain assumption and simplification.

To minimize the influences of friction force and gravity force, a compensate signal is set and merged with swept frequency input. The compensate signal is set based on the identified frictional force and gravity force in previous section. A sign switch block is used to guarantee that the friction compensate signal is opposite to actual friction force direction. Figure 4.5 shows the swept frequency input signal and corresponding response in both time and frequency domain.

It can be seen in figure 4.5a, system shows irregular response in time domain. The stage can only move with amplitude of 0.1mm after 160s even with the help of friction compensate signal. Similarly, the frequency response shown in figure 4.5b become hard to understand.

One possibility is that the friction force inside linear stage in not only related with local position but also related to the stage speed. This makes the friction force non-linear during open loop identification process. The non-linearity of friction force makes system hardly behave as a normal mass-spring-damping system.
4.1.4. Close loop identification

Since the open loop identification method does not work well, close loop identification method is proposed. Close loop identification is often used when system is unstable or the motion of system is restricted. The basic idea of close loop identification is deriving the plant transfer function by identifying sensitivity ($S(s)$) and process sensitivity ($PS(s)$) instead of measuring input and output of open loop directly. The configuration of close loop identification is demonstrated in Fig 4.6.

The relation between input ($u$) and disturbance ($d$) represents the sensitivity:

$$S(s) = \frac{u(s)}{d(s)} = \frac{1}{1 + C(s)H(s)}$$  \hspace{1cm} (4.8)

where $C(s)$ is the transfer function of PID controller and $H(s)$ is the transfer function of plant. Since the reference here is set to zero. The error can be represented as:

$$e = 0 - x = -x$$  \hspace{1cm} (4.9)

Hence the process sensitivity is:

$$PS(s) = \frac{-e(s)}{d(s)} = \frac{x(s)}{d(s)} = \frac{H(s)}{1 + C(s)H(s)}$$  \hspace{1cm} (4.10)

After deriving the sensitivity and process sensitivity, the transfer function of plant can described as:

$$\frac{PS(s)}{S(s)} = \frac{H(s)}{1 + C(s)H(s)} = H(s)$$  \hspace{1cm} (4.11)
4.2. Unilateral Controller Design

4.2.1. Control system overview

The basic idea of unilateral controller is set the human hand motion in translational direction as reference to compare with measured slave position. A controller is used to minimize the error between reference and measured feedback. The schematic is shown in Fig. 4.8.

4.2.2. Controller model

The control of system is implemented by a PI (Proportional-Integral) controller. As the friction force inside system makes plant over-damped, D(derivative) action is not added in controller. The controller can be expressed mathematically as:

\[ u(t) = K_p e(t) + K_i \int e(t) \, dt \]  \hspace{1cm} (4.12)

The controller output is combination of two terms. The I action compensate the static friction force to decrease error in low frequency, the proportional action take care the present error. The controller can also be
described in Laplace domain with a transfer function:

\[
C(s) = K_p + \frac{K_i}{s}
\]  

(4.13)

The task of local slave controller is to guarantee that the slave can follow human hand motion. Hence, the bandwidth of local slave controller should be at least higher than human hand maximum frequency. As different operators have different maximum frequency, the maximum frequency is considered in fastest situation (7Hz).

According to the measured data of frequency response in model identification section, the loop gain of plant in 7Hz is approximately 1.7. Hence the gain of controller can be derived as:

\[
K_p = \left. \frac{1}{|H(jw)|} \right|_{w=7 \times 2 \pi} \approx 0.6
\]

(4.14)

As an \(s\) term is added into denominator of transfer function, 90 deg of phase lag is added into system. In order not to make the open loop phase more negative than \(-180\) deg, the integral action should be stopped at 10% of bandwidth frequency, which can be expressed as:

\[
\omega_i = 0.1 \omega_c \approx 4.3 \text{ rad/s}
\]

(4.15)

Then the \(k_i\) is expressed as:

\[
K_i = \omega_i K_p = 2.58
\]

(4.16)

Hence, the exact transfer function of controller is:

\[
C(s) = 0.6 + \frac{2.6}{s}
\]

(4.17)

Figure 4.9 shows the controller response and theoretical open loop response with controller \(L(s) = \frac{1}{s}\). The open loop transfer function is the production of controller \(C(s)\) and the plant transfer function \(G(s)\):

\[
L(s) = C(s)G(s)
\]

(4.18)

### 4.2.3. Close loop response

The close loop response is identified by setting reference signal as a chirp signal. As human hand motion frequency can not be faster than 10 Hz, the input signal is chosen to be starting from 0.1Hz and ending at 11.6Hz with the amplitude of 0.2mm. Figure 4.10 depicts the close loop response in frequency domain. A peak with the amplitude of 1.3 appears around 6Hz. The presence of this peak is explained that the close loop system performed resonant behaviour at specific frequency(approximately 6 Hz). To compensate this peak, a pre-filter is designed and will be described in next section.
4.2. Unilateral Controller Design

4.2.4. Pre-filter design

The task of pre-filter is to decrease the loop gain around specific frequency so that the total close loop response magnitude can be smoothed. Based on the identified close loop response in figure 4.10, a peak of 1.3 around 6Hz is demanded to compensate. Hence, pre-filter magnitude behaviour in frequency domain should be 1/1.3 around 6Hz and 1 in rest frequency. Moreover, as the slope on left side of peak is +1 and slope of right side is -2, the slope of pre-filter should also be a inverse value to compensate respectively. Hence, the transfer function can be estimated as:

$$F(s) = \frac{s^2 + \omega \delta s + \omega^2}{s^2 + \omega s + \omega^2}$$  \hspace{1cm} (4.19)

Where $\omega$ is frequency of the peak, $\delta$ is the compensate ratio. After giving exact value to $\omega$ and $\delta$, the transfer function of pre-filter is:

$$F(s) = \frac{s^2 + 27.79s + 1471}{s^2 + 38.35s + 1471}$$  \hspace{1cm} (4.20)

Figure 4.11 demonstrates the performance of prefiltered close loop response compared with system without pre-filter. Around frequency of 6Hz, the magnitude of system is smoothed and the rest part of frequency domain is not influenced much by pre-filter. As for the phase, only area around peak value frequency (6Hz) is shifted lag or lead about 8 degrees.
4.3. Bilateral Controller Design

After a unilateral controller is designed to manage the motion following, a bilateral controller is designed to manage the position following and to present force feedback at master side simultaneously.

4.3.1. Control architecture

To help operator get the feeling of contact point, an alternative option is sending the measured force data directly to master device and the master will generate required Z-force (sensed insertion force) to human hand with four DC Motors. The configuration inside control is depicted in Fig.4.12.

![Control architecture diagram](image)

To clarify the control architecture used in Fig.4.12, the control architecture can also be represented in Lawrence style [12] in figure (2.6b). The basic concept of control architecture used in this thesis has no much difference with position-force control method. There is only one force feedback loop in system. The measured contact force at slave side is transmitted directly to master side. At the same time, position controller tries to the decrease position error with proportional gain and integral gain.
4.3.2. Proposed gain scheduling position controller design

In this section, a gain scheduling method is proposed to avoid the force instability when slave robot interacts with environment with high stiffness. Firstly, the interaction situation analysis is implemented to prove the unstability. Secondly, a gain scheduling method is designed to avoid unstability.

**Situation analysis**

As mentioned in local slave controller design part, a PI controller is used to make the slave device follow master device. The I action can compensate the friction force in low frequency to decrease steady state error. However, in haptic control situation, the slave device interacts with external environment, which means system is no more an isolated system. This indicts that the resistance forces, which stops slave device from reaching required position, become the sum of friction force and interaction force instead of only friction force.

Figure 4.13 demonstrates the situation when slave is interacting with stiff environment.

![force interaction diagram](image)

Figure 4.13: Force and position configuration when slave model interacts with environment. The reference \(X_r\) is the linear position of master device and measured position \(x\) is the position of slave robot. A PI controller (not displayed) will make use of the error to generate require actuation force \(F_a\).

The equation of slave motion based on figure 4.13 can be derived as:

\[
m\ddot{x} = F_a - F_e - F_f
\]

where \(F_a\) is actuation force, \(F_e\) is interaction force and \(F_f\) is the friction force.

The interaction force is related to the stiffness of environment, while the \(F_a\) is the actuation force which is determined based on equation (4.12). Therefore, the equation (4.21) can be further expressed as:

\[
m\ddot{x} = K_p e(t) + K_i \int e(t) dt - K_e \delta x - F_f
\]

where \(K_e\) is the stiffness of environment and \(\delta x\) is the deformation of environment. To simplify of circumstance, the friction force is assumed to be constant. When the acceleration of slave(\(\ddot{x}\)) is zero, the system is in equilibrium. The relation between actuation force(\(F_a\)) and interaction force(\(F_e\)) can be represented as:

\[
K_p e(t) + K_i \int e(t) dt = K_e \delta x + F_f
\]

Due to the environment's high stiffness, the deformation(\(\delta x\)) here varies with a small value. Hence, the deformation influence on position error \(e(t)\) can be neglected. Based on the relation equation between actuation force and interaction force, in equilibrium situation, when error is close to zero, the sum of interaction force and friction force can be regarded as zero. However, when slave is in contact with stiff environment where position error is a non-zero constant, the actuation force will keep increase due to the integral action of controller. Figure 4.14 displays a simulated actuation force when position error is a constant value. In practical, due to limitation of actuator, the force can not be that high. However, the increasing actuation force results in equivalently increasing interaction force which influences stability of system.
20 4. Controller Design

Figure 4.14: The simulated response of controller actuation force with $K_p = 0.6$ and $K_i = 2.58$. The error between desired position and present position is set as 1mm. The force increases with a slope of around $20 \, N/s$ and reaches $12 \times 10^3 \, N$ in 40 seconds.

Control strategy
To avoid this problem, the integral action in controller should be switched off when slave robot comes into contact with external environment. Figure 4.15 depicted the haptic system including gain scheduling part. After the integral action is switched off, only proportional controller works in haptic system. The connection between master and slave can be regarded as a virtual unidirectional spring whose stiffness is equal to the proportional gain of controller. Then, the interaction force with stiff environment in steady state can be represented as:

$$F_e = K_p e(t)$$  \hspace{1cm} (4.24)

where interaction force($F_e$) will be a stable value when position error is a constant.

4.3.3. Needle insertion with integrated haptic teleoperation system
In previous sections, the control architecture is designed and improved with gain scheduling. In this section, the integrated haptic teleoperation system will be used by operator to manipulate a needle into simulated human layer. The contact force and needle displacement will be measured to investigate the system performance.

Configuration description
Figure 4.16 demonstrated the needle insertion configuration from both front view and side view. The needle is actuated by the integrated haptic teleoperation system to insert through the "human skin" which is simulated by plastic membrane.

At master side, operator manipulates the action bar on master device to control needle to impale the "human skin ". Meanwhile, at slave side, the needle is actuated by controller to follow recorded human hand motion in translational direction.
4.3. Bilateral Controller Design

Test result

Figure 4.17b depicts the contact force and displacement of needle during whole needle insertion process. It can be observed that the displacement of needle and the contact force is influencing each other when the needle tip starts to touch the skin. When the time comes around 4.3s, the contact force starts to increase gradually and the speed of insertion is decreased simultaneously. Moreover, around 8.4s, the force is shapedly decrease and the position of needle goes deeper with a mount of 40mm, which means the needle just goes through the simulated human skin.

Discussion on force sensitivity

To analyse the feeling of operator, the operator force should be taken into account. The configuration on master side can be described with equation of motion:

\[ F_h - F_a = M_{master} \ddot{x} + C_{master} \dot{x} \]  \hspace{1cm} (4.25)

where \( F_h \) is force imposed operator, \( F_a \) is actuation force (sensed contact force), \( M_{master} \) is the inertia of master in translational direction and \( C_{master} \) is the damping.

Based on the equation of motion, the actual force the operator can feel is the sum of sensed contact force and force imposed by master device. In other words, when the contact force is comparable or far larger than force imposed by master device, the operator can recognize the environment force. However, when the contact force is far smaller, the operator can hardly detect the environment force.

It can be seen from figure 4.17b that the force imposed by master device stays around 0.2N in the beginning of needle insertion process and shows a impulse of 1N when the needle impales the simulated human skin. Compared with the sensed contact force during process, the imposed force is relatively low due to the low inertia and friction of master device.

Consequently, the force sensitivity of master side depends on the dynamic property of manipulator. The introduce of parallel mechanism in manipulator design decreases the inertia of master device, which makes the force sensitivity 0.2N approximately in this experiment.

4.3.4. Proposed Interaction Regulator Design

In previous section, the haptic teleperation is tested to manipulate needle to insert into simulated human skin. The process can be implemented safely and skin stiffness can be felt by operator stably. This is because the stiffness of human skin is much smaller than stiffness of controller, which means the influence of this soft environment (human skin) on needle motion is close to zero.

This section will start to testify the haptic system behaviour when slave needle interacts with stiff environment (for example a bone). After that, a regulation block is designed based on test result to regulate contact force.
4. Controller Design

Figure 4.17: (a) Instruction of sign of force and displacement and corresponding direction. The positive sign of displacement means the needle is moving down. And the positive sign of force means the direction of force is pointing up. (b) The force displacement plot during the needle insertion process. The force imposed by master is calculated based on the measured master device motion and identified master device model (see appendix G.3)

Interaction process without regulator

In order to build a sufficiently stiff environment, a glass box (see Fig 4.18a) is used to interact with slave robot in this experiment. Figure 4.18b describes contact force and the corresponding displacements of slave and master.

The contact force in this plot shows several impulses and the displacements decrease after every impulse happened. These impulses force makes the contact between slave robot and stiff environment unstable, which means the slave robot can not keep in contact with stiff environment with a certain contact force.

To regulate this unstable contact, what really happened during this process should be analysis first. It can be seen from this plot that the motion of slave follows master motion during whole process, which means the position controller works properly. Therefore, the sharp decrease motion after every impulse can be explain with the fact that the operator hand is pushed back by the impulse force from master device. Based on control architecture (Fig. 4.15), the measured contact force value on slave side is directly used to generate the same force on master side. Hence, the unstable contact is due to the fact that interaction is disturbed by the impulse force.
The formation of this impulse force is because that the generated force on master side cannot follow the real contact force between slave and environment perfectly. There is time delay between real contact force and simulated contact force and this time delay makes operator detect the contact late, which makes human hand (reference position) push further. The high stiffness of environment can generate high elastic force with a comparatively small deformation. Due to the time delay and high stiffness of environment, the measured force can jump to a force value of 20N in fractional second.

Therefore, either eliminating time delay or regulating contact force is a solution to this problem. As for time delay, it can be seen from figure 4.15 that there are force sensor, controller, motors and real time controller between real contact force and operator side. Every blocks have their bandwidth separately. It is possible to decrease time delay by replacing better device, however this is impossible to eliminate time delay absolutely.

On the other hand, the force regulating is a possible direction to solve the problem. By controlling the contact force, the force generated on operator side would also be regulated. The regulated force can keep the system in equilibrium with certain interaction force.

**Interaction analysis**

An interaction regulator is proposed to add into controller part. The basic idea of interaction regulator is adding measured contact force into position control loop as feedback with certain gain $K_f$ to weaken the stiffness of position controller (see Fig.4.19). The output of controller can be expressed as:

$$u(t) = K_p e(t) - K_f F_e^*$$  \hspace{1cm} (4.26)

where $u(t)$ is the output from controller, $K_f$ is force gain and $F_e^*$ is the measured contact force.

By replacing replacing $F_a$ in equation 4.21 with equation E.14, equation of slave motion can be written as:

$$m \ddot{x} = K_{motor}(K_p e(t) - K_f F_e^*) - F_e - F_f$$  \hspace{1cm} (4.27)

where $K_{motor}$ is motor constant.

In contact situation, the system is in equilibrium, which makes $\ddot{x}$ zero. Then equation can be written as:

$$K_{motor} K_p e(t) - F_f = K_{motor} K_f F_e^* + F_e$$  \hspace{1cm} (4.28)

For the sake of simplification, the measured force $F_e^*$ is assumed to be identical with real contact force $F_e$. Hence, the equation can be expressed as:

$$F_e = \frac{K_{motor} K_p e(t) - F_f}{K_{motor} K_f + 1}$$  \hspace{1cm} (4.29)

The motor constant is known as $140\,\text{N/V}$ and the friction force in certain area of stage is estimated around $20\,\text{N}$. If the position error is set to 1mm, the contact force can be expressed by $K_p$ and $K_f$ as:

$$F_e = \frac{140 K_p - 20}{140 K_f + 1}$$  \hspace{1cm} (4.30)

Figure 4.20 visualized the relation between Contact force ($F_e$) and two control gains ($K_p$ and $K_f$) based on the derived equation. It can observed that the contact force is proportional to position gain whereas the increase of force gain can weaken the contact force. The derived equation and plot can be used as a reference to adjust parameters in controller to achieve a desired force. However, as there are a few of simplification and
assumption contained in equation, manually parameters tuning process is still necessary to be combined with derived equation for designer in practical implementation.

**Practical Implementation**

The schematic of whole haptic teleoperation system with contact regulator is drawn in figure 4.21. What is notable is that a switch block is added in order to switch between position control mode, soft environment mode and stiff environment mode. The switch criteria is based on the measured contact force value. When the slave comes into contact with stiff environment, the position gain will be switched to 0.1 and the force gain (0.0714) will be enabled by switch block.

To test the performance of contact regulator, the system with regulator is manipulated by operator to interact with stiff environment (the same glass box used in last section).

Figure 4.20: The surface plot of contact force with respect to force gain and position gain.

![Image of surface plot](image)

Figure 4.20: The surface plot of contact force with respect to force gain and position gain.

Figure 4.21: The schematic of whole haptic teleoperation system with contact regulator. The strong gain \(P_{\text{strong}}\) is position gain when contacting with soft environment. The weak gain \(P_{\text{weak}}\) is position gain used in contact regulator mode.

Figure 4.21: The schematic of whole haptic teleoperation system with contact regulator. The strong gain \(P_{\text{strong}}\) is position gain when contacting with soft environment. The weak gain \(P_{\text{weak}}\) is position gain used in contact regulator mode.

Figure 4.22a shows the measured contact force and displacement of master and slave during the contact process. It can be seen from the plot that the contact force is regulated around 3N and slope of curve becomes smoother compared with the contact force in figure 4.18b. Moreover, the increase of the position error between master and slave can also cause the rise of contact force. Simultaneously, the slave position stays the same position as long as the slave starts to contact with stiff environment, which means the slave can contact with stiff environment stably with certain contact force.

Figure 4.22b describes the position controller, force regulator action and the combined action. It can be seen that the force regulator starts to work only when the interaction begins.
4.3. Bilateral Controller Design

(a) Force displacement plot.

(b) Input from position gain, force and the sum

Figure 4.22: The performance plot of system with force regulator.
Performance Evaluation

In the previous chapter, the complete bilateral controller is designed and tested in different situations. A few measured results are presented and analysed in order to improve system stability and robustness.

This chapter will focus on the performance evaluation of the haptic teleoperation system based on the measured result. Firstly, the position repeatability of the system in free air environment will be judged. After that, the simulated dynamic range of the system using different control architectures will be presented and discussed. Finally, the system stability will be discussed from the aspects of definition, identification and boundary condition.

5.1. Position repeatability of system in free air environment

To measure the repeatability of the system in free air environment, the slave is controlled to make 50 steps with amplitude of 1mm in 100 seconds. Figure 5.1a demonstrates the measured position and reference. The steady state errors of these 50 steps are collected and analysed in terms of error distribution. It can be observed from figure 5.1b that the probability density error mainly located at 0.005mm - 0.015mm range. The slave device is repeatable with steady state error of less than 0.02mm which is acceptable for tele-operation. The position error is mainly caused by local friction force (20-30N) and backlash inside linear stage.

![Figure 5.1a](image1.png)

(a) Steps of 1mm used to measure repeatability.

![Figure 5.1b](image2.png)

(b) Probability density of steady state error.

Figure 5.1

5.2. Dynamic range of system

The dynamic range of the system reflects the range of stiffness that the master can present to the operator, for all different environments[12]. The stiffness felt by operator in master side can be presented as:

\[
K_{op} = \frac{F_h}{X_h}
\]  

(5.1)
where $F_h$ is the force felt by operator and $X_h$ is the corresponding displacement. As no force sensor is available at master side, it is assumed that the master side and human hand are in equilibrium, which means the contact force is equal to force felt by operator.

Based on the concept in figure 2.5, the relation between slave position ($X_e$), environment force ($F_e$), master position ($X_h$) and human feeling force ($F_h$) can be represented in form of H-matrix:

$$\begin{bmatrix} F_h \\ -X_e \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \times \begin{bmatrix} X_h \\ F_e \end{bmatrix}$$  \hspace{1cm} (5.2)

The stiffness felt by operator then can be described by elements in H-matrix as:

$$K_{op} = \frac{F_h}{X_h} = \frac{h_{11} + (h_{11}h_{22} - h_{12}h_{21})K_e}{1 + h_{22}K_e}$$  \hspace{1cm} (5.3)

where $K_e$ is the stiffness of environment.

When the system is interacting stiff environment, the stiffness felt at master side can be estimated as:

$$K_{op, stiff} \approx \frac{h_{11}h_{22} - h_{12}h_{21}}{h_{22}}$$  \hspace{1cm} (5.4)

When the system is in free air, the stiffness felt by operator is:

$$K_{op, free} \approx h_{11}$$  \hspace{1cm} (5.5)

The dynamic range of system demonstrates the absolute difference value between $K_{op, stiff}$ and $K_{op, free}$ in frequency domain. The elements inside H-matrix can be derived based on schematic in figure 2.4 and control architectures in chapter 4. The details of derivation of H elements can be found in appendix G.

Figure 5.2 describes the dynamic ranges of system with and without interaction regulator. The result is simulated in MATLAB based on identified master device model and different gain values inside controller. By comparing the results in figure 5.2a and 5.2b, the dynamic range is decreased from 183dB to 150dB and the environment stiffness operator can feel is limited to approximately 1.2N/mm due to the introduce of interaction regulator. In other words, interaction regulator increased the system stability and robustness by sacrificing system dynamic range.

![Bode Diagram](image1.png)  \hspace{1cm} (a) The dynamic range (area between blue line and red line) of original control architecture in figure 4.12

![Bode Diagram](image2.png)  \hspace{1cm} (b) The dynamic range (area between blue line and red line) of control architecture with interaction regulator in figure 4.22a

Figure 5.2

5.3. Stability

5.3.1. Definition of stability

The stability of the system is necessary for operator to implement tele-manipulation safely. The definition of stability can be different based on what the system is used for. In this thesis, the haptic system is used to help clinicist implement needle insertion in human body. To avoid undesired damage to patients, both contact force and needle motion should be in control of operator for all different environments.
5.3. Stability

One reason for operator to lose the control of needle is the force with high increase speed and magnitude at master side, which makes operator can not response in time to hold joy stick of master device. Therefore, in this thesis, the magnitude of contact force and the variation speed of contact force are defined as states to represent system stability. A stability plot contained variation of interaction force and magnitude information of interaction force is defined to evaluate system stability (see Fig 5.3a).

To judge a system stable or not, the boundary condition of force and derivative force is required to be clarified (see Fig 5.3b). However, different operators have different capabilities of handling contact force. Hence, the boundary condition varies respect to different operators.

![Diagram](image)

Figure 5.3: (a) Defined stable criteria. The more upright state goes, the more unstable the system is. The closer to original point the state is, the more stable the system is. (b) The concept of boundary condition. When both force($F$) and derivative of force($dF/dt$) exceed certain value, the state of system can be judged as unstable.

### 5.3.2. Stability analysis

Figure 5.4 shows the stability plot of three different situations. The stability plots reflect the contact force and variation of contact force at every time point. The states in figure 5.4a and figure 5.4c stays in the region around original point during whole process, while the state in figure 5.4b travels away from original point and crosses upright area during certain period. Hence, the stiff environment contact process without interaction regulator is comparatively more unstable.

![Diagram](image)

Figure 5.4: The stability plot of three different situations experienced in this thesis.
Conclusion and Recommendation

6.1. Conclusion
In this thesis, a haptic teleoperation system for needle insertion has been integrated. With this system, operator can tele-manipulate needle motion under bandwidth of 7Hz. The force measured on needle tip can be felt by operator simultaneously. The fresh application of haptic technology in needle insertion carries injection therapy to next level and builds a solid research foundation for further development of 3 DOF steerable needle haptic system.

System Integration
Starting a stand-alone slave device with local controller, a haptic teleoperation system is integrated with a smart master device and real-time controller. For interfacing, every actuator and sensor in both master and slave parts are identified and tested separately.

Unilateral Controller design
After the integration of system, an unilateral position control system is designed to make slave robot track master device motion with bandwidth of 7Hz. By implementing and tuning proportional gain and integral gain in control schematic, an accuracy of 0.02mm is achieved.

Bilateral Controller Design
The bilateral controller successfully realizes haptic tele-manipulation of needle and gives operator right feeling when needle breaks through specific layer. The robustness of system is improved by introducing gain scheduling and interaction regulator. When slave contacts with stiff environment, the interaction regulator can stabilize the contact force around 5N.
6. Conclusion and Recommendation

Stability
The reasoning for instability in haptic teleoperation system is the high and fast jump contact force, which is caused by long delay time and high environmental stiffness. To visualize how stable the haptic teleoperation process is, a stability plot with contact force \( F \) as y-axis and time derivative of contact force as x-axis is defined. This plot can be used to indicate the state of system in terms of stability.

Conclusion: In this design, the operator can use the integrated system to manipulate the needle motion successfully and detect the contact force. How parameters of the system influence the performance and stability of system is investigated. What makes this work unique is getting an insight of how much clinical technology can benefit by introducing haptic technology. Also, many exploration experience in haptic field are gained, which is valuable for further research in the future.

6.2. Recommendations
After all the components are integrated and work together successfully, some evaluations and adaptations can be made to further improve the whole system performance and to contribute to future research and application of this field.

6.2.1. Recommendations considering slave part
- The ball screw system used in linear stage should be replaced by other linear actuation e.g, linear motor. The larger friction and non-linearity inside ball screw system decreased position accuracy and system performance. Hence, a linear actuation makes actuation mechanism more direct and improves the non-linearity.
- The position of stage should be sensed by position sensor directly instead of sensing the rotation of spindle. The indirect position measurement decreases the feedback sensitivity and accuracy.
- The mass of stage should be decreased to decrease the effect of inertia. During needle insertion, the overshoot caused by inertia would cause additional damage to patients.

6.2.2. Recommendations considering master part
The cable transmission 6.1 between lower leg and motor on the base should be redesigned to improve the stability and robustness. The encircled cable on motor is tensed with certain force so that the static force on motor axis is sufficient to actuate the lower leg. However, due to unperfect encirclement and too much or less tense force, the cable jumps from motor axis frequently or even snaps. Moreover, when master device is in equilibrium with hand with a large force, there will be a slip between cable and motor axis.

Some improvement plans are proposed to solve the present problem. Firstly, thicker cable should be used instead of the present cable to increase the strength and capacity. Secondly, some leading tracks (e.g., screw thread) should be made on motor axis to prevent side slip of cable. Figure 6.2 demonstrates one of the possible solutions.

6.2.3. Recommendation considering control architecture
- A pressure sensor should be mounted on manipulator side. With new added sensor, 4 channel control architecture proposed by Lawrence can be implemented, a better performance can be achieved.
- More switch modes should be designed. The state switch of controller can be smoother without jump signal during needle insertion process with more switch modes.
- The force sensor should be replaced by a better sensor with less noise.
Figure 6.1: The configuration of cable transmission in the device. (a) The front view of cable transmission. The lower leg and motor is connected with a cable. (b) The side view of cable transmission. The cable encircles both the axis of motor and lower leg so that the torque of motor can convert to lower leg with a factor of 7.

Figure 6.2: The axis of motor is cut with screw threads which fit with encircled cables.
Bibliography


Detailed wire connection

A.1. The schematic of wire connection

A.1.1. Wire connection of slave

The schematic of slave wire connection contained exact signal path from interfaces to interfaces is depicted in Fig.A.1.

Figure A.1: The schematic of wire connection in slave device

A.1.2. Wire connection of master

The schematic of slave wire connection contained exact signal path from interfaces to interfaces is depicted in Fig.A.2.
Figure A.2: The schematic of wire connection in master device
force sensor test

To collaborate the force and output voltage, preload needs to be added by using a preload screw and double leaf spring with certain stiffness. Figure B.1 demonstrates the configuration of test setup.

![Figure B.1: The configuration of preload. By rotating preload screw, the load force, which is provided by leaf spring, can be adjusted.](image)

Based on the equilibrium situation shown in above figure, the preload force can be calculated:

\[ F_{\text{pre}} = (X_o - X)k \]  \hspace{1cm} (B.1)

where \( k \) is the total stiffness of double leaf spring.

Hence, what force sensor output signal for now is the voltage corresponding to the preloaded force.

To collaborate the force and output voltage, a certain preload force needs to be added first. Then a mass with known property would be added. The gravity caused by the mass would make the output signal of force sensor change a little bit.

The force analysis of the situation is demonstrated in figure B.2.

As the configuration is still in equilibrium position and no movement happened compared with the previous situation, the modification is the nature position. The new nature position \( X'_o \) become a little lower than the original one \( X_o \), because the applied mass. The equation is:

\[ Mg = k(X_o - X'_o) \]  \hspace{1cm} (B.2)

On the other hand, the new preload force (output of force sensor) can also be derived:

\[ F'_{\text{pre}} = k(X'_o - X) \]  \hspace{1cm} (B.3)

By subtracting the first equation and the third equation and combining the representative of the applied mass, the relation between the change of output voltage and the applied mass can be figured out:
Case the applied mass value is known, the linear relation between force and voltage can be found.

\[ F_{pre} - F'_{pre} = Mg \]  \hspace{1cm} (B.4)
In this chapter, a low pass filter used in force feedback is designed to filter out the noise contained in measured force signal. Firstly, the measured signal from force sensor is analysed in frequency domain. Secondly, based on the signal frequency distribution, a low pass filter is designed by using toolbox in MATLAB.

C.1. Noisy signal analysis

The noisy signal from force sensor is measured when no pressure is added on force sensor. Figure C.1 shows the measured signal in both time domain and frequency domain.

The measured voltage noise ranges from -0.05v to +0.03V. The frequencies of signal mainly locate around 50Hz and 100Hz. In order to get improve the quality of signal, a low pass filter with cut off frequency lower than 50Hz should be designed.

C.2. Filter Design

The filter is designed via DSP toolbox in MATLAB. The parameters is tuned based on the frequency response of filter. A trade-off between signal quality and delay time needs to be implemented due to the fact that time delay of force feedback signal is critical in system stability. Hence, the time delay is restricted to be no more than 0.02s.

C.2.1. Frequency Response of Filter

To make the delay time no more than 0.02s, the order of filter should be no more than 20, since the sample time is 0.001s. To optimize the quality of signal, a filter should be designed so that there are anti-windups in 50Hz and 100Hz in frequency domain. The frequency response of filter is manually tuned based on the
requirement proposed mentioned. Figure C.2 presented the frequency response and corresponding parameters after manually tuning. The anti-windup around 50Hz and 100Hz would compensate the main noise source.

(a) Filter parameters in toolbox panel.  
(b) Frequency response of filter.  

Figure C.2

C.2.2. Performance measurement

Figure C.3 demonstrates the performance of designed filter in time domain and frequency domain. Compared with measured signal in figure ??, figure ?? shows that the amplitude in 0Hz remains the same, while the amplitude at 50Hz is compensated and decreased from 0.045 to approximately 0. In time domain, the noise amplitude is decreased from 0.045 to 0.005.

(a) Filter performance in time domain  
(b) Filter performance in frequency domain  

Figure C.3
Simulink Block Diagram of Controller

This chapter will describe the detailed design of controller. The Bachmann controller is a real-time controller which can be programmed with Simulink by using coupling software (M-target). A overview of block diagram of whole control architecture in Simulink will be shown first and the rest details inside subsystem will be presented secondly.
D.1. Whole block diagram

Figure D.1: The whole block diagram programmed in Simulink
D.2. Master part

Figure D.2: Master kinematics part in Simulink

D.3. Control part

Figure D.3: Control part in Simulink
Figure D.4: Security part in Simulink

D.4. Security part

D.5. Slave part

Figure D.5: Slave part in Simulink
E

Data Sheet
# E.1. Encoder (slave part)

## Automation / Mini

### Type 2RMHF

- Hollow Shaft Encoder - Ø 24 mm
- Hollow Bore: Ø 2 mm to Ø 1/4 inch
- Resolution up to 7,500 ppr
- IP 64 rating *(IP 50 for flat cable option)*

### Electrical Specifications

<table>
<thead>
<tr>
<th>Code:</th>
<th>Incremental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution:</td>
<td>1 to 7,500 ppr (pulses per revolution)</td>
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<tr>
<td>Supply Voltage:</td>
<td><strong>4,5 Vdc min. to 30 Vdc max.</strong> (45 mA max. - no load)</td>
</tr>
<tr>
<td>Output Voltage:</td>
<td><strong>Low: 500 mV max. at 10 mA</strong>&lt;br&gt;<strong>High: (V&lt;sub&gt;a&lt;/sub&gt; – 0,6) at -10 mA</strong>&lt;br&gt;<strong>V&lt;sub&gt;a&lt;/sub&gt; – 1,3) at -25 mA</strong></td>
</tr>
<tr>
<td>Output Current:</td>
<td>30 mA max. load per output channel **</td>
</tr>
<tr>
<td>Frequency Response:</td>
<td>200 kHz max. **</td>
</tr>
<tr>
<td>Output Format:</td>
<td>Two channel (A, B) quadrature with Index (Z) and optional complementary (A-, B-, Z-) outputs</td>
</tr>
<tr>
<td>Phase Sense:</td>
<td>A leads B clockwise (CW) from the mounting end of the encoder</td>
</tr>
<tr>
<td>Index:</td>
<td>Gated with Channels A and B high</td>
</tr>
<tr>
<td>Accuracy:</td>
<td>+/- 26 arc-sec.</td>
</tr>
<tr>
<td>Outputs:</td>
<td>ASIC Push pull and Differential OL7272 Push-pull and Differential Line Driver 26C31 Differential Line Driver 5V output (with 5V input)</td>
</tr>
<tr>
<td>Electrical Protection:</td>
<td>Reverse polarity and output short circuit protected</td>
</tr>
<tr>
<td>Noise Immunity:</td>
<td>Tested to EN61000-6-2 : 2005 (industrial environments) Electromagnetic compatibility (EMC) and EN 61000-6-3 : 2007 (residential, commercial, and light-industrial environments) for Electromagnetic compatibility (EMC)</td>
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</tbody>
</table>

### Mechanical Specifications

<table>
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<tr>
<th>Material:</th>
<th>Housing: Brass&lt;br&gt;Cap: Electroplated Steel&lt;br&gt;Aluminum (flat cable option)&lt;br&gt;Hollow Shaft: Brass</th>
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</thead>
<tbody>
<tr>
<td>Weight:</td>
<td>Encoder: ~ 35 gr (1,23 oz)&lt;br&gt;Cable: 50 gr / meter (1,76 oz / meter)</td>
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<tr>
<td>Bearing Life:</td>
<td>&gt; 1,9 x 10&lt;sup&gt;10&lt;/sup&gt; revolutions at rated load</td>
</tr>
<tr>
<td>Bearing Pre-Load:</td>
<td>1 to 3600 ppr 4000 to 5000 ppr 7500 ppr 4 (N) 7 (N) 10 (N)</td>
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<tr>
<td>Shaft Speed:</td>
<td>12,000 rpm (max.)</td>
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<tr>
<td>Starting Torque:</td>
<td>&lt; 0,005Nm (0,708 oz-in) at 25° C</td>
</tr>
<tr>
<td>Mass Moment of Inertia:</td>
<td>1,0 gcm² (1,42 x 10⁻⁵ oz-in-sec²)</td>
</tr>
<tr>
<td>Hollow Shaft Loads:</td>
<td>Axial: 20 N (4,5 lbs) max.&lt;br&gt;Radial: 20 N (4,5 lbs) max.</td>
</tr>
</tbody>
</table>

### Environmental Specifications

| Operating Temp.: | -40° to +85° C |
| Storage Temp.:   | -40° to +85° C |
| Shock:           | 100 G / 11 ms |
| Vibration:       | 10-2000 Hz / 10 G |
| Bump:            | 10 G / 16 ms (1000 x 3 axis) |
| Humidity:        | 98 % RH without condensation |
| IP Rating:       | IP 64 / Nema 4 (approx.)<br>IP 50 / Nema 5 (approx.) – flat cable |

### Connection Options

| Cable:          | 8 leads (0,05 mm², 30 AWG) - Differential 5 leads (0,14 mm², 26 AWG) - Standard twisted pairs; shielded |
| Connector:      | 5-pin M9<br>8-pin M9 |
| Flat Cable:     | 10 lead flat cable with IDC connector |

**= It is recommended user not to combine max. value for all 3 parameters
Line Drivers are available for the HEDM-5500 series encoders. The line driver offers enhanced performance when the encoder is used in noisy environments, or when it is required to drive long distances.

The HEDL-556x series utilizes an industry standard line driver IC, AM26C31Q, which provides complementary outputs for each encoder channel. Thus, the output of the line driver encoder is A, A, B, B. Suggested line receivers are 26LS32 and 26LS33.

For additional information, please refer to:
HEDM-55xx/56xx datasheet.

Features
- Available on Encoder Kit Housing (HEDM-5500 Series)
- Complementary Outputs
- Industry Standard Line Driver IC
- Single 5 V Supply
- Onboard Bypass Capacitor
- Operating Temperature up to 70°C

Note: Avago Technologies encoders are not recommended for use in safety critical applications. E.g. ABS braking systems, power steering, life support systems and critical care medical equipment. Please contact sales representative if more clarification is needed.

Device Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Characteristic</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Termination</td>
<td>10 conductor ribbon cable with 10 position IDC connector</td>
<td>See pinout</td>
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<tr>
<td>Electrical Outputs</td>
<td>Complementary outputs: A, A, B, B, I, I</td>
<td>I and I available only on three channel encoders</td>
</tr>
<tr>
<td>Line Driver Components</td>
<td>AM26C31Q line driver IC, decoupling capacitor on PC board.</td>
<td></td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40°C to 70°C</td>
<td></td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>-40°C to 70°C</td>
<td></td>
</tr>
</tbody>
</table>

ESD WARNING: NORMAL HANDLING PRECAUTIONS SHOULD BE TAKEN TO AVOID STATIC DISCHARGE.
E.3. Actuator (slave part)

EC 40 Ø40 mm, brushless, 120 Watt

Part Numbers

Motor Data

Values at nominal voltage
1 Nominal voltage V 12 18 21 30 24 36 42 48 48 48 48 48 48 48
2 No load speed rpm 10300 12000 10400 11600 10300 9830 10400 7560 10300 5930 5420 3530 3110 2020
3 No load current mA 886 754 515 426 443 275 258 139 222 97.8 86.2 48.6 41.3 24.4
4 Nominal speed rpm 9050 10900 9240 10500 9160 8710 9290 6450 9190 4830 4290 2400 1990 893
5 Nominal torque (max. continuous torque) mNm 107 113 116 120 123 122 127 123 130 126 127 129 129
6 Nominal current (max. continuous current) A 10.4 8.62 6.46 5.24 5.78 3.76 3.40 2.22 2.96 1.77 1.57 1.03 0.92 0.599
7 Stall torque mNm 985 1340 1150 1420 1210 1200 1280 940 1270 743 639 410 370 237
8 Starting current A 89.2 94.4 60.1 57.9 55.0 34.6 33.5 15.7 28.8 9.72 7.65 3.21 2.56 1.07
9 Max. efficiency % 81 83 84 84 83 84 82 84 81 80 77 75 72

Characteristics
10 Terminal resistance phase to phase £Ω 0.134 0.151 0.349 0.518 0.436 1.04 1.25 3.07 8.62 6.46 5.24 5.78 3.76
11 Terminal inductance phase to phase mH 0.0266 0.0439 0.0797 0.132 0.106 0.263 0.319 0.788 0.425 0.127 0.161 0.212
12 Torque constant mNm/A 11.0 14.2 19.1 24.6 22.1 34.7 38.2 60.1 44.1 7.64 8.35 7.12 4.48 3.07
13 Speed/torque gradient rpm/mNm 865 873 500 389 433 275 250 159 216 125 114 74.8 66.0 43.2
14 Mechanical time constant ms 9.39 9.05 9.13 8.20 8.55 8.26 8.20 8.12 8.16 8.07 8.59 8.76 8.56 8.75
15 Rotor inertia gcm² 85.0 85.0 85.0 85.0 85.0 85.0 85.0 85.0 85.0 85.0 85.0 85.0 85.0 85.0

Operating Range

n (rpm)
120 W
1000
800
600
400
200
100
80
60
40
20
10
0
10 1200 W
6000 8000 10000 12000 14000 16000 18000

maxon Modular System

Planetary Gearhead Ø42 mm 3 - 16 Nm Page 270
Planetary Gearhead Ø52 mm 4 - 30 Nm Page 273

Recommended Electronics:
ESCON 50/5 Page 321
DEC5 Module 50/5 Page 325
EPOS2 24/5, 50/5 Page 334
EPOS2 P 24/5 Page 334

Notes

Encoders HED_5540
3 channels
Page 386/388
Resolver Res 26
10 V
Page 316
Brake AB 28
0.4 Nm
Page 348

maxon special program

May 2013 edition / subject to change
E.4. Actuator (master part)

**RE 30** Ø30 mm, Precious Metal Brushes, 15 Watt

---

**Part Numbers**

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**Motor Data (provisional)**

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<th>4</th>
<th>5</th>
<th>6</th>
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<th>13</th>
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<td>Voltage V</td>
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<td>9</td>
<td>12</td>
<td>18</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>12</td>
<td>18</td>
<td>0.378</td>
<td>0.63</td>
<td>1.45</td>
<td>2.47</td>
<td>19.9</td>
<td>25.9</td>
<td>39.8</td>
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<tr>
<td>Current mA</td>
<td>41.6</td>
<td>33.4</td>
<td>20.8</td>
<td>15.9</td>
<td>53</td>
<td>53</td>
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<td>316</td>
<td>370</td>
<td>330</td>
<td>393</td>
<td>479</td>
<td>369</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>Speed rpm</td>
<td>2870</td>
<td>3310</td>
<td>2870</td>
<td>3190</td>
<td>53</td>
<td>53</td>
<td>53</td>
<td>53</td>
<td>316</td>
<td>370</td>
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<td>393</td>
<td>479</td>
<td>369</td>
<td>240</td>
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<tr>
<td>Stall torque mNm</td>
<td>2.7</td>
<td>2.08</td>
<td>1.35</td>
<td>1</td>
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<td>1.7</td>
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<tr>
<td>Stall current A</td>
<td>15.9</td>
<td>14.3</td>
<td>8.29</td>
<td>7.3</td>
<td>15.9</td>
<td>14.3</td>
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<td>15.9</td>
<td>14.3</td>
<td>8.29</td>
<td></td>
</tr>
<tr>
<td>Max. efficiency %</td>
<td>90</td>
<td>91</td>
<td>90</td>
<td>91</td>
<td>90</td>
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<td>91</td>
<td>90</td>
<td>91</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

**Characteristics**

| Terminal resistance Ω | 0.378 | 0.63 | 1.45 | 2.47 | 0.0703 | 0.119 | 0.281 | 0.513 | 19.9 | 25.9 | 39.8 |
| Terminal inductance mH  | 0.0703 | 0.119 | 0.281 | 0.513 | 19.9 | 25.9 | 39.8 |
| Torque constant mNm/A   | 9.1 | 8.97 | 8.71 | 8.14 | 9.1 | 8.97 | 8.71 | 8.14 |
| Speed / torque gradient rpm/mNm | 3.42 | 3.14 | 3.02 | 2.96 | 3.42 | 3.14 | 3.02 | 2.96 |
| Mechanical time constant ms | 35.9 | 33.5 | 33.1 | 34.7 | 35.9 | 33.5 | 33.1 | 34.7 |
| Motor inertia g ms²      | 35.9 | 33.5 | 33.1 | 34.7 | 35.9 | 33.5 | 33.1 | 34.7 |

**Mechanical data (ball bearings)**

| 23 | 24 | 25 | 26 | 27 | 28 |
| Max. speed 3300 rpm | Axial play at axial load 0.05 - 0.15 mm | Radial play 0.025 mm | Max. axial load (dynamic) 5.6 N | Max. force for pinion fits (static) 110 N | Max. radial load, 5 mm from flange 28 N |

**Operating Range**

Continuous operation

In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient. = Thermal limit.

Short term operation

The motor may be briefly overloaded (recurring).

Assigned power rating

---

**Specifications**

| 17 | 18 | 19 | 20 | 21 | 22 |
| Thermal resistance housing-ambient 6.8 K/W | Thermal resistance winding-housing 1.7 K/W | Thermal time constant winding 16.9 s | Thermal time constant motor 593 s | Ambient temperature -20…+85°C | Max. winding temperature +100°C |

**Thermal data**

Max. speed 3300 rpm

Axial play at axial load 0.05 - 0.15 mm

Radial play 0.025 mm

Max. axial load (dynamic) 5.6 N

Max. force for pinion fits (static) 110 N

Max. radial load, 5 mm from flange 28 N

**Other specifications**

| 29 | 30 | 31 | 32 |
| Number of pole pairs 13 | Number of commutator segments 260 g | Weight of motor 260 g |

Values listed in the table are nominal. Explanation of the figures on page 107.

**Option**

Preloaded ball bearings

---

**Mechanical Modular System**

| 33 | 34 | 35 | 36 |
| Planetary Gearhead 0.32 mm | 0.75 - 4.5 Nm | Page 370 | Page 322 |

**Recommended Electronics:**

<table>
<thead>
<tr>
<th>Notes</th>
<th>Page 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoder M6 256 - 1024 CPT, 3 channels</td>
<td>Page 356</td>
</tr>
<tr>
<td>Encoder HED_5540 500 CPT, 3 channels</td>
<td>Page 362/364</td>
</tr>
</tbody>
</table>

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**Motor Data (provisional)**

| 1906_DC_motor.indd   138 07.05.15   09:22 |

---

**maxon DC motor**

---

May 2015 edition / subject to change
E.5. Amplifier (slave part)

maxon motor

Operating Instructions 4-Q-EC Servoamplifier DES 50/5
June 2007 Edition / document number 811734_PDF_E - 01 / subject to change

2 Performance Data

2.1 Electrical data

Supply voltage $V_{CC}$ (Ripple < 5%) ............................................................... 12 - 50 VDC
Max. output voltage .................................................................................... 0.9 $V_{CC}$
Max. output current $I_{out}$ ........................................................................ 15 A
Continuous output current $I_{cont}$ ........................................................... 5 A
Switching frequency .................................................................................. 50 kHz
Max. efficiency .......................................................................................... 92 %
Band width current controller ................................................................. 1 kHz
Max. speed (motor with 1 pole pair) ....................................................... 25 000 rpm
Built-in motor choke per phase ............................................................... 160 µH / 5 A

2.2 Inputs

“Set value” ................................................. configurable by DIP Switch S9: -10 ... +10 V $R_I = 80 \, k\Omega$
“Enable” ................................................................................................. +2.4 ... +50 VDC $R_I = 22 \, k\Omega$
“Digital 1” (Switch “Monitor n” / “Monitor I”) ......................................... +2.4 ... +50 VDC $R_I = 22 \, k\Omega$
“Digital 2” (Switch speed-/current controller) ........................................ +2.4 ... +50 VDC $R_I = 50 \, k\Omega$
“STOP” ................................................................................................... +2.4 ... +50 VDC $R_I = 22 \, k\Omega$
Encoder signals .......................................................................................... A, B, I, f max. 1 MHz
Hall sensor signals .................................................................................... Hall sensor 1, Hall sensor 2, Hall sensor 3
CAN ID (CAN identification) ................................................................. configured by DIP Switch S1...7
$ID = 1 ... 127$ (binary coded)

2.3 Outputs

Monitor ................................................................................................. configurable by DIP Switch S10: -10 ... +10 V $R_I = 1 \, k\Omega$, $f_s = 900 \, Hz$
Status reading “Ready” ........................................................................... open collector max. 30 VDC $I_0 < 20 \, mA$

2.4 Voltage outputs

Encoder supply voltage .............................................................................. +5 VDC, max. 100 mA
Hall sensors supply voltage ......................................................................... +5 VDC, max. 50 mA

2.5 Interfaces

RS232 ....................................................................................................... RsD; TxD (max. 115 200 bit/s)
CAN ......................................................................................................... CAN_H (high); CAN_L (low) (max.1 Mbit/s)

2.6 Trim potentiometers

$n_{max}$, Offset, $I_{max}$, gain

2.7 LED indicator

Bi-colour LED ....................................................................................... READY / ERROR (green = READY, red = ERROR)

2.8 Ambient temperature / Humidity range

Operating ................................................................................................. -10 ... +45°C
Storage ..................................................................................................... -40 ... +85°C
non condensing ....................................................................................... 20 ... 80 %

2.9 Mechanical data

Weight ..................................................................................................... approx. 410 g
Dimensions ............................................................................................ see dimension drawing, chapter 9

2.10 Connections

PCB clamps ............................................................................................. Power (6 poles), Signal (18 poles)
Pitch ........................................................................................................ 3.5 mm
suitable for wire cross section ........................................0.14 ... 1 mm² multiple-stranded or 0.14 ... 1.5 mm² single wire
Encoder .................................................................................................. Plug DIN41651 (10 poles)
for flat band cable, pitch 1.27 mm, AWG28
## 2 Specifications

### 2.1 Technical Data

<table>
<thead>
<tr>
<th>Electrical Rating</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal operating voltage</td>
<td>+V_Cc</td>
</tr>
<tr>
<td>Absolute operating voltage</td>
<td>+V_Cc_{min} / +V_Cc_{max}</td>
</tr>
<tr>
<td>Output voltage (max.)</td>
<td>0.98 x +V_Cc</td>
</tr>
<tr>
<td>Output current I_{cont} / I_{max} (&lt;20 s)</td>
<td>5 A / 15 A</td>
</tr>
<tr>
<td>Pulse Width Modulation frequency</td>
<td>53.6 kHz</td>
</tr>
<tr>
<td>Sampling rate PI current controller</td>
<td>53.6 kHz</td>
</tr>
<tr>
<td>Sampling rate PI speed controller</td>
<td>5.36 kHz</td>
</tr>
</tbody>
</table>

| Max. speed DC motor        | limited by max. permissible speed (motor) and max. output voltage (controller) |
| Max. speed EC motor        | 150'000 rpm (1 pole pair) |
| Built-in motor choke       | 3 x 30 μH; 5 A |

<table>
<thead>
<tr>
<th>Inputs &amp; Outputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Input 1</td>
<td>resolution 12-bit; −10…+10 V; differential</td>
</tr>
<tr>
<td>Analog Input 2</td>
<td>resolution 12-bit; −4…+4 V; referenced to GND</td>
</tr>
<tr>
<td>Analog Output 1</td>
<td>+2.4…+36 VDC (R = 38.5 kΩ)</td>
</tr>
<tr>
<td>Analog Output 2</td>
<td></td>
</tr>
<tr>
<td>Digital Input 1</td>
<td>H1, H2, H3</td>
</tr>
<tr>
<td>Digital Input 2</td>
<td></td>
</tr>
<tr>
<td>Digital Input/Output 3</td>
<td></td>
</tr>
<tr>
<td>Digital Input/Output 4</td>
<td></td>
</tr>
<tr>
<td>Hall sensor signals</td>
<td></td>
</tr>
<tr>
<td>Encoder signals</td>
<td>A, A, B, B, (max. 1 MHz)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Outputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary output voltage</td>
<td>+5 VDC (I \leq 10 mA)</td>
</tr>
<tr>
<td>Hall sensor supply voltage</td>
<td>+5 VDC (I \leq 30 mA)</td>
</tr>
<tr>
<td>Encoder supply voltage</td>
<td>+5 VDC (I \leq 70 mA)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potentiometers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentiometer P1 (on board)</td>
<td>240°; linear</td>
</tr>
<tr>
<td>Potentiometer P2 (on board)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motor Connections</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DC motor</td>
<td>+ Motor, − Motor</td>
</tr>
<tr>
<td>EC motor</td>
<td>Motor winding 1, Motor winding 2, Motor winding 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interface</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>USB 2.0 / USB 3.0</td>
<td>full speed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Status Indicators</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>green LED</td>
</tr>
<tr>
<td>Error</td>
<td>red LED</td>
</tr>
</tbody>
</table>
### E.7. Bachmann Controller (Digital interfaces)

**Inputs**

<table>
<thead>
<tr>
<th>Digital Input/Output Module</th>
<th>DIO216</th>
<th>DIO216/4</th>
<th>DIO232</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>0 to 16</td>
<td>16 to 32</td>
<td></td>
</tr>
<tr>
<td>Internal resistance</td>
<td>approx. 6.8 kΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-level</td>
<td>0 to +5 VDC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-level</td>
<td>+15 to +34 VDC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input delay (typ./max. through filter)</td>
<td>600 µs / 800 µs</td>
<td>39 µs to 365 ms</td>
<td></td>
</tr>
<tr>
<td>Interrupt inputs</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Input delay (typ.)</td>
<td>50 µs</td>
<td>35 µs</td>
<td></td>
</tr>
<tr>
<td>Trigger edge</td>
<td>positive / negative / both edge(s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jitter of the input signals</td>
<td>20 µs</td>
<td>6 µs</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 128: Technical data (DIO216/x, DIO232) - Inputs
### Outputs

<table>
<thead>
<tr>
<th>Digital Input/Output Module</th>
<th>DIO216</th>
<th>DIO216/4</th>
<th>DIO232</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
<td>0 to 16</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Separate output groups</strong></td>
<td>1 to 16</td>
<td>1 to 4</td>
<td>1 to 8</td>
</tr>
<tr>
<td></td>
<td>5 to 8</td>
<td>9 to 12</td>
<td>9 to 16</td>
</tr>
<tr>
<td></td>
<td>9 to 16</td>
<td>13 to 16</td>
<td></td>
</tr>
<tr>
<td><strong>Output voltage</strong></td>
<td>typ. +24 VDC (+18 to +34 VDC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Output current per channel</strong></td>
<td>1 A</td>
<td>0.5 A</td>
<td></td>
</tr>
<tr>
<td><strong>Output current per group</strong></td>
<td>≤ 12 A</td>
<td>≤ 4 A</td>
<td></td>
</tr>
<tr>
<td><strong>Output current per group (UL/CUL)</strong></td>
<td>≤ 10 A</td>
<td>≤ 4 A</td>
<td></td>
</tr>
<tr>
<td><strong>Output current per module</strong></td>
<td>≤ 12 A</td>
<td>≤ 16 A</td>
<td>≤ 8 A</td>
</tr>
<tr>
<td><strong>Inductive shutoff (at 24 V, max. output current, 0.1 Hz)¹</strong></td>
<td>350 mH</td>
<td>1.6 H</td>
<td></td>
</tr>
<tr>
<td><strong>Short-circuit capability/overload</strong></td>
<td>Yes, active power limit, thermally secured</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Refresh cycle/switching frequency</strong></td>
<td>1 ms / 1 kHz with ohmic resistive load only</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Switching delay (typ./max.)</strong></td>
<td>Low -&gt; High</td>
<td>220 / 430 µs at 1 A, Ohmic load</td>
<td>65 / 115 µs at 0.5 A, Ohmic load</td>
</tr>
<tr>
<td></td>
<td>High -&gt; Low</td>
<td>220 / 430 µs at 1 A, Ohmic load</td>
<td>50 / 80 µs at 0.5 A, Ohmic load</td>
</tr>
</tbody>
</table>

¹By externally connecting to free-wheeling diodes, varistors or RC elements, the inductive shutoff capacity can be increased. It should be remembered that it takes longer to shut off inductive loads.

Tab. 129: Technical data (DIO216/x, DIO232) – Outputs
E.9. Bachmann Controller (Analog interfaces)

Hardware (product description)  Analog input/output modules

Analog inputs

<table>
<thead>
<tr>
<th>Analog input/output module</th>
<th>AIO288/x</th>
</tr>
</thead>
<tbody>
<tr>
<td>±10 V</td>
<td>±1 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>≤ 8</th>
<th>≤ 4</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input type</td>
<td>Differential or single-ended</td>
<td>-</td>
<td>2 or 4 wire technology</td>
<td></td>
</tr>
<tr>
<td>Measuring range</td>
<td>-10 to +10 V</td>
<td>-1 to +1 V</td>
<td>0 to 20 mA</td>
<td>-100 to +500 °C</td>
</tr>
<tr>
<td>Input impedance</td>
<td>&gt; 100 kΩ</td>
<td>243 Ω</td>
<td>&gt; 100 kΩ</td>
<td></td>
</tr>
<tr>
<td>digital resolution</td>
<td>14 Bit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of LSB</td>
<td>1.22 mV</td>
<td>122 µV</td>
<td>1.22 µA</td>
<td>0.1 K</td>
</tr>
<tr>
<td>Error at 25°C</td>
<td>±0.025 % from U_E (20 V)</td>
<td>±0.05 % from U_E (2 V)</td>
<td>±0.1 % from I_E (20 mA)</td>
<td>±0.1 % from T_E (600 K)</td>
</tr>
<tr>
<td>Problems</td>
<td>STANDARD</td>
<td>coldclimate design (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preselection filter</td>
<td>Low pass 1st order, f_G = ~1.5 kHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>±0.005 % from U_E (20 V) / K</td>
<td>±0.01 % from I_E (20 mA) / K</td>
<td>±0.01 % / K from T_E (600 K)</td>
<td></td>
</tr>
<tr>
<td>Linearity error</td>
<td>±0.025 % from U_E (20 V)</td>
<td>±0.01 % from I_E (20 mA)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Repetition accuracy</td>
<td>±0.025 % from U_E (20 V)</td>
<td>±0.01 % from I_E (20 mA)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Stabilization time</td>
<td>typically 30 min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowed common mode voltage</td>
<td>±1 V</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common mode rejection voltage</td>
<td>&gt; 50 dB</td>
<td>&gt; 60 dB (typ. &gt; 60 dB)</td>
<td>&gt; 60 dB</td>
<td>&gt; 60 dB</td>
</tr>
<tr>
<td>Cross-talk attenuation between the channels</td>
<td>&gt; 60 dB</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**E.10. Bachmann Controller (Analog interfaces)**

### Voltage outputs

<table>
<thead>
<tr>
<th>Analog input/output module</th>
<th>AIO288/x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>≤ 8</td>
</tr>
<tr>
<td>Output voltage</td>
<td>±10 V</td>
</tr>
<tr>
<td>Output impedance</td>
<td>Output is readjusted up to ±2 mA</td>
</tr>
<tr>
<td>Short circuit capability</td>
<td>Yes, permanent</td>
</tr>
<tr>
<td>Digital resolution</td>
<td>14 Bit</td>
</tr>
<tr>
<td>Value of LSB</td>
<td>1.22 mV</td>
</tr>
<tr>
<td>Error at 25°C</td>
<td>±0.025 % from $U_A$ (20 V) &lt;sup&gt;1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Problems</td>
<td>STANDARD</td>
</tr>
<tr>
<td></td>
<td>coldclimate design</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>STANDARD</td>
</tr>
<tr>
<td></td>
<td>coldclimate design</td>
</tr>
<tr>
<td>Linearity error</td>
<td>≤ ±0.025 % from $U_A$ (20 V) &lt;sup&gt;1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Repetition accuracy</td>
<td>≤ ±0.025 % from $U_A$ (20 V) &lt;sup&gt;1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Allowed common mode voltage</td>
<td>±1 V</td>
</tr>
<tr>
<td>Common mode rejection voltage</td>
<td>&gt; 60 dB</td>
</tr>
<tr>
<td>Cross-talk attenuation between the channels</td>
<td>&gt; 60 dB</td>
</tr>
<tr>
<td>Settling time</td>
<td>≤ 400 µs (change over the full range)</td>
</tr>
<tr>
<td>Overshoot</td>
<td>≤ ±1 % (change over the full range)</td>
</tr>
<tr>
<td>Ripple</td>
<td>±0.015 %</td>
</tr>
<tr>
<td>External proof voltage</td>
<td>-15 to +28 V</td>
</tr>
<tr>
<td>Refresh cycle time</td>
<td>200 µs</td>
</tr>
</tbody>
</table>

1) only valid for DC  
2) $U_A$ = output range  
3) as of function code 110.xxx/driver V2.13  
 coldclimate design

Tab. 370: AIO288/x technical data - Voltage outputs
### E.11. Bachmann Controller (Encoder interfaces)

#### Incremental encoder interface

<table>
<thead>
<tr>
<th>Counter module</th>
<th>RS422 level</th>
<th>HTL level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Resolution of the counters</td>
<td>32 Bit</td>
<td></td>
</tr>
<tr>
<td>Input signals</td>
<td>A-, A+, B+, B-, N-, N+</td>
<td></td>
</tr>
<tr>
<td>Input frequency</td>
<td>≤ 1 MHz</td>
<td>≤ 300 kHz</td>
</tr>
<tr>
<td>Preselection filter</td>
<td>Low pass 1st order, $f_g = 10$ MHz</td>
<td></td>
</tr>
<tr>
<td>Input impedance, static</td>
<td>≥ 5 kΩ</td>
<td>3.6 kΩ</td>
</tr>
<tr>
<td>AC termination</td>
<td>121 Ω in series with 1 nF</td>
<td>n.a.</td>
</tr>
<tr>
<td>Input level</td>
<td>Low</td>
<td>According to RS422 standard</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Signal evaluation</td>
<td>1-2-4-fold edge analysis or pulse direction mode</td>
<td></td>
</tr>
<tr>
<td>Take over of the counter by external trigger</td>
<td>For positive edge of the trigger input</td>
<td></td>
</tr>
<tr>
<td>Synchronization</td>
<td>For negative edge of the SYNC pulse</td>
<td></td>
</tr>
<tr>
<td>Referencing of counter</td>
<td>Via software, zero pulse, initiator or initiator and zero pulse</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 629: CNT204/x, CNT204/H technical data – incremental encoder interface
E.12. Bachmann Controller (Encoder interfaces)

Digital inputs

<table>
<thead>
<tr>
<th>Counter module</th>
<th>CNT204/x</th>
<th>CNT204/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>4 (2, if INC inputs are used)</td>
<td></td>
</tr>
<tr>
<td>Resolution of the counters</td>
<td>32 Bit</td>
<td></td>
</tr>
<tr>
<td>Input frequency</td>
<td>≤ 5 kHz</td>
<td></td>
</tr>
<tr>
<td>Pulse length</td>
<td>≥ 100 µs</td>
<td></td>
</tr>
<tr>
<td>Preselection filter</td>
<td>Low-pass 1st order, fₖ = 100 kHz</td>
<td></td>
</tr>
<tr>
<td>Preselection filter, digital</td>
<td>Programmable 183.11 Hz to 46.88 kHz</td>
<td></td>
</tr>
<tr>
<td>Input impedance</td>
<td>4.4 kΩ</td>
<td></td>
</tr>
<tr>
<td>Input level</td>
<td>Low: 0 &lt; Uₑ &lt; +5 V, High: +15 V &lt; Uₑ &lt; +34 V</td>
<td></td>
</tr>
<tr>
<td>Counting pulse</td>
<td>For positive edge at the counter input</td>
<td></td>
</tr>
<tr>
<td>Synchronization</td>
<td>For negative edge of the SYNC pulse</td>
<td></td>
</tr>
<tr>
<td>Referencing of counter</td>
<td>Via software</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 630: CNT204/x, CNT204/H technical data – digital inputs

Period measurement

<table>
<thead>
<tr>
<th>Counter module</th>
<th>RS 422 inputs</th>
<th>HTL inputs</th>
<th>Digital inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference frequency</td>
<td>24 MHz ±100 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>41.7 ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measuring range</td>
<td>Cycle duration: 1 µs to 178 s, Frequency: 0.006 Hz to 1 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.33 µs to 178 s, Frequency: 0.006 Hz to 300 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 µs to 178 s, Frequency: 0.006 Hz to 5 kHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 631: CNT204/x, CNT204/H technical data – period measurement
E.13. Linear stage

PRO115 Series

**Mechanical Bearing, Ball-Screw Stage**

Nine models with travels from 50 mm to 600 mm
Speeds up to 300 mm/s
Side seal design with hard-cover
Low-cost; high performance
Long-life linear motion guide bearing system

The PRO115 is Aerotech’s smallest hard cover, side-sealed stage design. Competitive pricing coupled with Aerotech’s reputation for producing high-quality linear motion devices make the PRO115 an attractive stage for medium-performance applications.

**Rugged Construction**

The hard-cover design provides protection from debris. The robust aluminum cover is hard-coated to provide a scratch-resistant surface.

The side seals keep dirt and particulates out of the stage and protect the bearing surfaces from contamination. The vertical orientation of the seals easily deflects debris away from the stage. Competitive top-seal designs can collect debris, resulting in the eventual failure and replacement of the sealing mechanism.

**NEMA 23 Flange-Mount**

The PRO115 has a NEMA 23 flange-mounting interface for attachment of a wide variety of Aerotech and third-party motors. Aerotech can provide brush, brushless, and stepper motors preconfigured and mounted directly to the stage for integration with Aerotech controls. Or the stage can be purchased without the motor for the attachment of third-party motors.

**Easily Accessible Mounting**

The mounting holes in the PRO115 base are accessible from the outside of the stage for ease of integration. The cover does not have to be removed when mounting the stage to a bread-board or when attaching multiple stages together in an X/Y/Z system. The tabletop is available with both metric and English hole patterns and can be ordered with brush attachments to clear debris that may collect on the hard cover. Tabletops with hole patterns that allow the direct attachment of Aerotech’s ADRS, ACS-LP, and AGR series rotary stages are available.

**Configuration Options**

Aerotech’s BM or BMS series brushless servomotors with square-wave encoder output provide a net resolution of 0.5 micron. An optional analog output encoder can be coupled with external interpolation electronics to provide higher resolution. A holding brake can be added to the motor for vertical applications. A motor fold-back kit is available for space-constrained applications to reduce the overall stage length.

Cantilevered load capability of the PRO115.
## PRO115 Series SPECIFICATIONS

<table>
<thead>
<tr>
<th>Basic Model</th>
<th>PRO115-50</th>
<th>PRO115-100</th>
<th>PRO115-150</th>
<th>PRO115-200</th>
<th>PRO115-250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Travel</td>
<td>50 mm</td>
<td>100 mm</td>
<td>150 mm</td>
<td>200 mm</td>
<td>250 mm</td>
</tr>
<tr>
<td>Drive System</td>
<td>Ball Screw/Brushless Servomotor</td>
<td>Up to 2.3 A</td>
<td>Up to 1.8 A</td>
<td>Noncontact Rotary Encoder</td>
<td>Noncontact Rotary Encoder</td>
</tr>
<tr>
<td>Bus Voltage</td>
<td>Up to 320 VDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous Current</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Acceleration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>5 mm/rev lead</td>
<td>5 mm/rev lead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Travel Speed (1)</td>
<td>300 mm/s (12 in/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>±6 µm</td>
<td>±6 µm</td>
<td>±8 µm</td>
<td>±8 µm</td>
<td>±10 µm</td>
</tr>
<tr>
<td>Bidirectional Repeatability</td>
<td>±1 µm</td>
<td>±1 µm</td>
<td>±2 µm</td>
<td>±2 µm</td>
<td>±3 µm</td>
</tr>
<tr>
<td>Straightness and Flatness</td>
<td>3 µm</td>
<td>5 µm</td>
<td>6 µm</td>
<td>10 µm</td>
<td>10 µm</td>
</tr>
<tr>
<td>Nominal Stage Weight Less Motor</td>
<td>4.0 kg (8.8 lb)</td>
<td>4.4 kg (9.7 lb)</td>
<td>4.8 kg (10.6 lb)</td>
<td>5.3 kg (11.7 lb)</td>
<td>5.8 kg (12.8 lb)</td>
</tr>
<tr>
<td>With Motor</td>
<td>5.1 kg (11.2 lb)</td>
<td>5.5 kg (12.1 lb)</td>
<td>5.9 kg (13.0 lb)</td>
<td>6.4 kg (14.1 lb)</td>
<td>6.9 kg (15.2 lb)</td>
</tr>
<tr>
<td>Construction</td>
<td>Black Anodized Aluminum Body with Hardcoated Tabletop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Excessive duty cycle may impact stage accuracy.
2. Payload specifications are for single-axis system and based on ball screw and bearing life of 2500 km (100 million inches) of travel.
3. Specifications are for single-axis systems, measured 25 mm above the tabletop. Performance of multi-axis systems is payload and workpoint dependent. Consult factory for multi-axis or non-standard applications.

### PRO125 Series

<table>
<thead>
<tr>
<th>Basic Model</th>
<th>PRO115-300</th>
<th>PRO115-400</th>
<th>PRO115-500</th>
<th>PRO115-600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Travel</td>
<td>300 mm</td>
<td>400 mm</td>
<td>500 mm</td>
<td>600 mm</td>
</tr>
<tr>
<td>Drive System</td>
<td>Ball Screw/Brushless Servomotor</td>
<td>Up to 2.3 A</td>
<td>Up to 1.6 A</td>
<td>Noncontact Rotary Encoder</td>
</tr>
<tr>
<td>Bus Voltage</td>
<td>Up to 320 VDC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous Current</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Acceleration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>5 mm/rev lead</td>
<td>5 mm/rev lead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Travel Speed (1)</td>
<td>300 mm/s (12 in/s)</td>
<td>250 mm/s (10 in/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>±10 µm</td>
<td>±12 µm</td>
<td>±14 µm</td>
<td>±16 µm</td>
</tr>
<tr>
<td>Bidirectional Repeatability</td>
<td>±1 µm</td>
<td>±1 µm</td>
<td>±2 µm</td>
<td>±2 µm</td>
</tr>
<tr>
<td>Straightness and Flatness</td>
<td>12 µm</td>
<td>16 µm</td>
<td>18 µm</td>
<td>20 µm</td>
</tr>
<tr>
<td>Nominal Stage Weight Less Motor</td>
<td>6.2 kg (13.6 lb)</td>
<td>7.1 kg (15.6 lb)</td>
<td>7.9 kg (17.4 lb)</td>
<td>8.8 kg (19.4 lb)</td>
</tr>
<tr>
<td>With Motor</td>
<td>7.3 kg (16.1 lb)</td>
<td>8.2 kg (18.0 lb)</td>
<td>9.0 kg (19.8 lb)</td>
<td>9.9 kg (21.8 lb)</td>
</tr>
<tr>
<td>Construction</td>
<td>Black Anodized Aluminum Body with Hardcoated Tabletop</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
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1. Excessive duty cycle may impact stage accuracy.
2. Payload specifications are for single-axis system and based on ball screw and bearing life of 2500 km (100 million inches) of travel.
3. Specifications are for single-axis systems, measured 25 mm above the tabletop. Performance of multi-axis systems is payload and workpoint dependent. Consult factory for multi-axis or non-standard applications.
E.14. Force sensor

MODEL LSB200
Jr. Miniature S-Beam Load Cell

SPECIFICATIONS

PERFORMANCE
- Nonlinearity: ±0.1% of RO
- Hysteresis: ±0.1% of RO
- Nonrepeatability: ±0.05% of RO

ELECTRICAL
- Rated Output (RO): See chart on third page
- Excitation (VDC or VAC): 10 max
- Bridge Resistance: See chart on third page
- Insulation Resistance: ≥500 MOhm @ 50 VDC
- Connection: #29 AWG, 4 conductor, spiral shielded silicone cable, 5 ft (1.5 m) long
- Wiring/Connector Code: WC1

MECHANICAL
- Weight (approximate): 0.3 oz (9 g)
- Safe Overload: 1000% of RO
  200% tension only (50–100 lb)
- Material: Aluminum (10 g–10 lb), stainless-steel (25–100 lb)
- IP Rating: IP40

TEMPERATURE
- Operating Temperature: -60 to 200°F [-50 to 93°C]
- Compensated Temperature: 60 to 160°F [15 to 72°C]
- Temperature Shift Zero: ±0.01% of RO/°F [0.018% of RO/°C]
- Temperature Shift Span: ±0.02% of Load/°F [0.036% of Load/°C]

CALIBRATION
- Calibration Test Excitation: 5 VDC
- Calibration (standard): 5-pt Tension
- Calibration (available): Compression
F.1. Forward Kinematics of Manipulator

Listing F.1: N_3DOF_FWkin.m

```matlab
function X = N_3DOF_FWkin(q, X_old)

X = X_old;
theta = X(1);
phi = X(2);
z = X(3);

p = N_3DOF_p(phi,theta,z);
q_old = N_3DOF_INVkin(p,theta,phi);

act_errors = q-q_old(:,1);
it = 1;

while act_errors.' * act_errors > 1e-9 && it < 6

    %define new state
    q1_1 = q_old(1,1);
    q1_2 = q_old(1,2);
    q2_1 = q_old(2,1);
    q2_2 = q_old(2,2);
    q3_1 = q_old(3,1);
    q3_2 = q_old(3,2);
    q4_1 = q_old(4,1);
    q4_2 = q_old(4,2);
    q4_3 = q_old(4,3);

    %determine local Jacobian numerically
    Jmin1a = N_3DOF_Jmin1a(phi,q1_1,q1_2,q2_1,q2_2,q3_1,q3_2,q4_1,q4_2,q4_3,theta);
    Ja = pinv(Jmin1a(:,[1,2,6]));

    act_errors = q-q_old(:,1)

    % direction vector required because grasping is negative Pgamma
    X = X + Ja*act_errors;

    theta = X(1);

    it = it + 1;
end
```

63
phi = X(2);
z = X(3);
p = N_3DOF_p(phi,theta,z);
q_old = N_3DOF_INVkin(p,theta,phi);
it = it+1;
end

function \[q\text{.}num\] = N_3DOF_INVkin(p,theta,phi)

% Calculates the joint angles from the end-effector position
% This script is developed for the 4DOF steerable needle master device
% V01 based on invKin of 4DOF SN
% V02 adapted to script based on H-matrices with all links on X-axis
% V03 trying to fix issue with leg 2
% V04 adjusting to optimization

% repeat set values
lnk1 = 0.1646;
lnk2 = 0.3674;
Cbase = 0.07;

%%%%%%%%%%%%%%%%%%%%%
% legs 
%%%%%%%%%%%%%%%%%%%%%

% introduce empty variable matrices
bpsq = zeros(1,4); % the squared distance from actuator to platform
alpha = zeros(1,4); % the inner angle in the triangle formed by leg
beta = zeros(1,4); % the angle between the base and line bpsq
q_num = zeros(4,6); % empty matrix to store calculated link angles

% introduce dependent variables
b = [0,Cbase,0,−Cbase;−Cbase,0,Cbase,0; 0,0,0,0];

% determine angles
for i = 1

bpsq(i) = (p(2,i)−b(2,i))^2+(p(3,i)−b(3,i))^2;
alpha(i) = acos((lnk2^2−lnk1^2−bpsq(i))/(-2*lnk1*sqrt(bpsq(i))));
beta(i) = atan2(p(3,i)−b(3,i),p(2,i)−b(2,i));

% calculate thetai1 angle
q_num(i,1) = pi+beta(i) + alpha(i);

% calculate thetai2 angle
if bpsq(i) <= lnk1^2+lnk2^2
    q_num(i,2) = pi + asin(sqrt(bpsq(i))/lnk2 * sin(alpha(i)));
else
    q_num(i,2) = 2*pi - asin(sqrt(bpsq(i))/lnk2 * sin(alpha(i)));
end

q_num(i,3) = 7*pi/2 + theta − q_num(i,1) − q_num(i,2);
q_num(i,4) = phi;
for i = 2
    bpsq(i) = (p(1,i)−b(1,i))^2+(p(3,i)−b(3,i))^2;
    alpha(i) = acos((lnk2^2−lnk1^2−bpsq(i))/(-2*lnk1*sqrt(bpsq(i))));
    beta(i) = atan2(p(3,i)−b(3,i),p(1,i)−b(1,i));

    %calculate theta1 angle
    q_num(i,1) = 2*pi − beta(i) + alpha(i);

    %calculate theta2 angle
    if bpsq(i) <= lnk1^2+lnk2^2
        q_num(i,2) = pi + asin(sqrt(bpsq(i))/lnk2 * sin(alpha(i)));
    else
        q_num(i,2) = 2*pi − asin(sqrt(bpsq(i))/lnk2 * sin(alpha(i)));
    end

    % found using dot product between local Z and platform Z
    q_num(i,3) = 7*pi/2 − q_num(i,1) − q_num(i,2) + ...
                 atan(tan(phi)/cos(theta));

    q_num(i,4) = −atan(sin(theta)*cos(phi)/...
                 (cos(q_num(i,1) + q_num(i,2) + ...
                 q_num(i,3))*sin(phi) − sin(q_num(i,1) + ...
                 q_num(i,2) + q_num(i,3))*...)
                 cos(theta)*cos(phi));

    % using dot product between local X (or Y) and platform Z
    if theta*phi >= 0
        q_num(i,5) = −acos((cos(theta))/cos(q_num(i,4)));
    else
        q_num(i,5) = acos((cos(theta))/cos(q_num(i,4)));
    end
end

for i = 3
    bpsq(i) = (p(2,i)−b(2,i))^2+(p(3,i)−b(3,i))^2;
    alpha(i) = acos((lnk2^2−lnk1^2−bpsq(i))/(-2*lnk1*sqrt(bpsq(i))));
    beta(i) = atan2(p(3,i)−b(3,i),p(2,i)−b(2,i));

    %calculate theta1 angle
    q_num(i,1) = 2*pi − beta(i) + alpha(i);

    %calculate theta2 angle
    if bpsq(i) <= lnk1^2+lnk2^2
        q_num(i,2) = pi + asin(sqrt(bpsq(i))/lnk2 * sin(alpha(i)));
    else
        q_num(i,2) = 2*pi − asin(sqrt(bpsq(i))/lnk2 * sin(alpha(i)));
    end

    q_num(i,3) = 7*pi/2 − theta − q_num(i,1) − q_num(i,2);
    q_num(i,4) = −phi;
end

for i = 4
    % compensation for fact that link1 of leg1 is rotated at second
% joint.
l2_xsq = lnk2^2-p(2,i)^2;

bpsq(i) = (p(1,i)-b(1,i))^2+(p(3,i)-b(3,i))^2;
alpha(i) = acos((l2_xsq-lnk1^2-bpsq(i))/(-2*lnk1*sqrt(bpsq(i))));

beta(i) = atan2(p(3,i)-b(3,i),p(1,i)-b(1,i));

%calculate theta11 angle
q_num(i,1) = pi + beta(i) + alpha(i);

%calculate theta12 angle
if bpsq(i) <= lnk1^2+l2_xsq
    q_num(i,2) = pi + asin(sqrt(bpsq(i)/l2_xsq) * sin(alpha(i)));
else
    q_num(i,2) = 2*pi - asin(sqrt(bpsq(i)/l2_xsq) * sin(alpha(i)));
end

%calculate theta13 angle only for leg 4
q_num(i,3) = -asin(p(2,i)/lnk2);

%theta1_4 needs to be solved using the tangent half-angle
A14 = sin(q_num(i,1)+q_num(i,2))*sin(phi)-...
cos(q_num(i,1)+q_num(i,2))*cos(theta)*cos(phi);   
B14 = -sin(q_num(i,1)+q_num(i,2))*cos(q_num(i,3))*cos(theta)*cos(phi)-...
cos(q_num(i,1)+q_num(i,2))*cos(q_num(i,3))*sin(phi)+...
sin(q_num(i,1)+q_num(i,2))*sin(theta)*cos(phi);   
C14 = -sin(q_num(i,1)+q_num(i,2))*sin(phi)+...
cos(q_num(i,1)+q_num(i,2))*cos(theta)*cos(phi);
t14 = -(B14)*sqrt((B14)^2-2*A14*C14))/A14;
q_num(i,4) = 2*atan(t14);

%theta1_5 needs to be solved using the tangent half-angle
A15 = -sin(phi)*cos(q_num(i,1)+q_num(i,2))*sin(q_num(i,3))-...
cos(phi)*cos(theta)*sin(q_num(i,3))*sin(q_num(i,1)+q_num(i,2))-...
cos(phi)*sin(theta)*cos(q_num(i,3));
B15 = sin(phi)*cos(q_num(i,3))*cos(q_num(i,4))*cos(q_num(i,1)+q_num(i,2))-...
sin(q_num(i,1)+q_num(i,2))*sin(q_num(i,4))-...
cos(phi)*sin(theta)*cos(q_num(i,3))*cos(q_num(i,1)+q_num(i,2))-...
cos(phi)*cos(theta)*cos(q_num(i,3))*cos(q_num(i,1)+q_num(i,2))-...
cos(phi)*cos(theta)*sin(q_num(i,3))*sin(q_num(i,1)+q_num(i,2))-...
cos(phi)*sin(theta)*cos(q_num(i,3));
C15 = sin(phi)*cos(q_num(i,1)+q_num(i,2))*sin(q_num(i,3))+...
cos(phi)*cos(theta)*sin(q_num(i,3))*sin(q_num(i,1)+q_num(i,2))+...
cos(phi)*cos(theta)*sin(q_num(i,3));
if abs(A15) < 1e-18
    t15 = 0;
else
    t15 = -(B15)/A15;
end
q_num(i,5) = 2*atan(t15);
\[
\theta_1 \text{ needs to be solved using the tangent half-angle}
\]

\[
A_{16} = \sin(\theta_1) \sin(q_{num(i,1)}+q_{num(i,2)}) \cos(q_{num(i,3)}) \sin(q_{num(i,4)}) - \\
\sin(\theta_1) \cos(q_{num(i,1)}+q_{num(i,2)}) \cos(q_{num(i,4)}) + \\
\cos(\theta_1) \sin(q_{num(i,3)}) \sin(q_{num(i,4)});
\]

\[
B_{16} = \sin(\theta_1) \sin(q_{num(i,1)}+q_{num(i,2)}) (\cos(q_{num(i,3)}) \cos(q_{num(i,4)}) + \\
\sin(q_{num(i,3)}) \cos(q_{num(i,5)}) \sin(q_{num(i,1)}+q_{num(i,2)}) \sin(q_{num(i,4)}) \sin(q_{num(i,5)}) + \\
\cos(q_{num(i,3)}) \cos(q_{num(i,4)}) \sin(q_{num(i,5)}) - \cos(q_{num(i,3)}) \cos(q_{num(i,5)}) + \\
\sin(q_{num(i,1)}+q_{num(i,2)}) \cos(q_{num(i,3)}) \sin(q_{num(i,5)}) + \\
\sin(q_{num(i,3)}) \cos(q_{num(i,4)}) \sin(q_{num(i,5)}) - \cos(q_{num(i,3)}) \cos(q_{num(i,5)}) + \\
\cos(q_{num(i,3)}) \cos(q_{num(i,5)}) - \cos(q_{num(i,3)}) \cos(q_{num(i,5)});
\]

\[
C_{16} = -\sin(\theta_1) \sin(q_{num(i,1)}+q_{num(i,2)}) \cos(q_{num(i,3)}) \sin(q_{num(i,4)}) - \\
\sin(\theta_1) \cos(q_{num(i,1)}+q_{num(i,2)}) \cos(q_{num(i,4)}) - \\
\cos(\theta_1) \sin(q_{num(i,3)}) \sin(q_{num(i,4)});
\]

\[
\text{if abs}(A_{16}) < 1e^{-18}
\]

\[
t16 = 0;
\]

\[
\text{else}
\]

\[
t16 = (-B_{16}-\sqrt{(B_{16})^2-2A_{16}C_{16}})/A_{16};
\]

\[
\text{end}
\]

\[
q_{num(i,6)} = 2*\text{atan}(t16);
\]

\[
\text{end}
\]

Listing F3: N_3DOF_Jmin1a.m.m

\[
\begin{align*}
\text{function } & Jmin1a = \text{N}_{\text{3DOF}}\_\text{Jmin1a}(\phi_i, q_{1_1}, q_{1_2}, q_{2_1}, q_{2_2}, q_{3_1}, q_{3_2}, q_{4_1}, q_{4_2}, q_{4_3}, \theta) \\
\text{N}_{\text{3DOF}}\_\text{JMIN1A} & \\
\text{JMIN1A} = \text{N}_{\text{3DOF}}\_\text{JMIN1A}((\phi_i, q_{1_1}, q_{1_2}, q_{2_1}, q_{2_2}, q_{3_1}, q_{3_2}, q_{4_1}, q_{4_2}, q_{4_3}, \theta)) \\
\text{This function was generated by the Symbolic Math Toolbox version 6.1.} \\
\text{15-Apr-2015 16:09:32} \\
t2 &= \cos(q_{1_1}); \\
t3 &= \cos(q_{1_2}); \\
t4 &= \sin(q_{1_1}); \\
t5 &= \sin(q_{1_2}); \\
t6 &= t2.*t3; \\
t14 &= t4.*t5; \\
t7 &= t6-t14; \\
t8 &= \sin(\theta); \\
t9 &= \cos(\theta); \\
t10 &= t2.*t5; \\
t11 &= t3.*t4; \\
t12 &= t10+t11; \\
t13 &= t9.*t12.*(2.7e1./2.0e2); \\
t15 &= t4.*1.646e-1; \\
t16 &= t2.*t5.*3.674e-1; \\
t17 &= t3.*t4.*3.674e-1; \\
t26 &= t8.*(2.7e1./2.0e2); \\
t18 &= t15+t16+t17-t26; \\
t19 &= t2.*1.646e-1; \\
t20 &= t9.*(2.7e1./2.0e2); \\
t21 &= t2.*t3.*3.674e-1; \\
t29 &= t4.*t5.*3.674e-1; \\
t22 &= t19-t20+t21-t29; \\
t23 &= t12.*t22;
\end{align*}
\]
t27 = t7.*t18;
t28 = t7.*t8.*(2.7e1./2.0e2);
t24 = t13+t23–t27–t28;
t25 = 1.0./t24;
t30 = sin(phi);
t31 = cos(phi);
t32 = cos(q2.1);
t33 = sin(q2.2);
t34 = t32.*t33;
t35 = cos(q2.2);
t36 = sin(q2.1);
t37 = t35.*t36;
t38 = t34+t37;
t39 = t32.*t35;
t41 = t33.*t36;
t40 = t39–t41;
t42 = t9.*t30.*t40.*(2.7e1./2.0e2);
t43 = t31.*t38.*(2.7e1./2.0e2);
t44 = t36.*1.646e–1;
t45 = t32.*t33.*3.674e–1;
t46 = t35.*t36.*3.674e–1;
t55 = t9.*t30.*(2.7e1./2.0e2);
t47 = t44+t45+t46–t55;
t48 = t40.*t47;
t49 = t31.*(2.7e1./2.0e2);
t50 = t32.*1.646e–1;
t51 = t33.*t36.*3.674e–1;
t56 = t32.*t35.*3.674e–1;
t52 = t49–t50+t51–t56;
t53 = t38.*t52;
t54 = tan(theta);
t57 = t42–t43+t48+t53;
t58 = 1.0./t57;
t59 = cos(q3.1);
t60 = cos(q3.2);
t61 = sin(q3.1);
t62 = sin(q3.2);
t63 = t59.*t60;
t69 = t61.*t62;
t64 = t63–t69;
t65 = t59.*t62;
t66 = t60.*t61;
t67 = t65+t66;
t68 = t9.*t67.*(2.7e1./2.0e2);
t70 = t8.*t64.*(2.7e1./2.0e2);
t71 = t61.*1.646e–1;
t72 = t59.*t62.*3.674e–1;
t73 = t60.*t61.*3.674e–1;
t74 = t20+t71+t72+t73;
t75 = t61.*t62.*3.674e–1;
t80 = t59.*1.646e–1;
t81 = t59.*t60.*3.674e–1;
t76 = t20+t75–t80–t81;
t79 = t64.*t74;
t82 = t67.*t76;
t77 = t68+t70–t79–t82;
t78 = 1.0./t77;
t83 = cos(q4_3);
t84 = cos(q4_1);
t85 = cos(q4_2);
t86 = sin(q4_1);
t87 = sin(q4_2);
t88 = t83.*t84.*t87;
t89 = t83.*t85.*t86;
t90 = t88+t89;
t91 = t83.*t84.*t85;
t94 = t83.*t86.*t87;
t92 = t91-t94;
t93 = sin(q4_3);
t95 = t86.*1.646e-1;
t96 = t83.*t84.*t85.*3.674e-1;
t97 = t83.*t85.*t86.*3.674e-1;
t98 = t55+t95+t96+t97;
t99 = t83.*t86.*t87.*3.674e-1;
t100 = t49+t99-t106-t107;
t101 = t31.*t90.*(2.7e1./2.0e2);
t102 = t9.*t30.*t92.*(2.7e1./2.0e2);
t103 = t101+t102-t105-t108;
t104 = 1.0./t103;
t109 = t31.*t93.*(2.7e1./2.0e2);
t110 = t109-t8.*t30.*t92.*(2.7e1./2.0e2);
Jmin1a = reshape([t25.*(t13-t7.*t8.*(2.7e1./2.0e2))+t7.*t9.*t25.*t30.*(2.7e1./2.0e2),
(t8.*t30.*t38.*(2.7e1./2.0e2))./(t42+t48+t53-t31.*t38.*(2.7e1./2.0e2)),
-t78.*(t68+t70)-t9.*t30.*t64.*t78.*(2.7e1./2.0e2),t104.*(t8.*t30.*t90.*(2.7e1./2.0e2)+t9.*t30.*t93.*(2.7e1./2.0e2)),
t7.*t25.*t31.*t54.*(2.7e1./2.0e2),t58.*(t42-t43)+t8.*t30.*t40.*t54.*t58.*(2.7e1./2.0e2),
t31.*t54.*t64.*t78.*(-2.7e1./2.0e2),
-t104.*(t101+t102)+t54.*t104.*t110+t31.*t54.*t93.*t104.*(2.7e1./2.0e2),0.0,18.*t30.*t40.*t58.*(2.7e1./2.0e2),0.0,t104.*t110,0.0,-t40.*t58,0.0,-
t92.*t104,-t7.*t25,0.0,t64.*t78,-t93.*t104,-t12.*t25,t38.*t58,-t67.*t78,-t90.*t104
],[4, 6]);

function ckin_p = N_3DOF_p(phi,theta,z)

% This function was generated by the Symbolic Math Toolbox version 6.1.
% 15-Apr-2015 16:09:29

t2 = cos(phi);
t3 = t2.*(2.7e1./2.0e2);
t4 = cos(theta);
t5 = sin(phi);
t6 = sin(theta);
ckin_p = reshape([0.0,t4.*(-2.7e1./2.0e2)-t5.*t6.*(-2.7e1./2.0e2),t6.*(-2.7e1./2.0e2)+z,
(t3-0.0,z-t4.*t5.*(-2.7e1./2.0e2),0.0,t4.*(-2.7e1./2.0e2)-t5.*t6.*(-2.7e1./2.0e2),t6
.*(2.7e1./2.0e2)+z,-t3,t5.*t6.*(-2.7e1./1.0e2),z+t4.*t5.*(2.7e1./2.0e2)],[3, 4]);
E.2. Motor torque calculation of manipulator

```matlab
function tau = fcn(X, Fm)
    %#codegen

    theta = X(1);
    phi = X(2);
    z = X(3);

    p = N_3DOF_p(phi,theta,z);
    q = N_3DOF_INVkin(p,theta,phi);

    q1_1 = q(1,1);
    q1_2 = q(1,2);
    q2_1 = q(2,1);
    q2_2 = q(2,2);
    q3_1 = q(3,1);
    q3_2 = q(3,2);
    q4_1 = q(4,1);
    q4_2 = q(4,2);
    q4_3 = q(4,3);

    %determine local Jacobian numerically
    Jmin1a = N_3DOF_Jmin1a(phi,q1_1,q1_2,q2_1,q2_2,q3_1,q3_2,q4_1,q4_2,q4_3,theta);
    JaT = pinv(Jmin1a(:,[1,2,6]).');

    % consider transmission ratio
    tau = (JaT*Fm)./7;
end
```
Derivation of elements inside H matrix

This chapter described the derivation details of elements inside H matrix. The transfer function of master and slave device estimated based on the identified data. The elements inside H matrix also depends on different control architectures. The elements will be derived based on different controller separately.

G.1. Control architecture without interaction regulator

Based on the control architecture above, the force felt by operator is the total force of force imposed by master displacement and the simulated force generated by motors of master device. Hence, the equation of motion at master side can be derived as:

\[ F_h = Z_m X_h - K_f F_e \]  \hspace{1cm} (G.1)

where \( Z_m \) is inverse of master device transfer function \( (Z_m = M_m s^2 + C_m s) \).

Correspondingly, the displacement of slave robot is the close loop system response plus the influence of environment force to system. Therefore, the equation of motion at slave side is:

\[ X_e = H_{\text{close loop}} X_h - \frac{H_{\text{close loop}} F_e}{K_p} \]  \hspace{1cm} (G.2)

where \( H_{\text{close loop}} \) is the transfer function of close loop position control system. By combining equations G.1 and G.2, the H matrix can be derived:

\[
\begin{bmatrix}
F_h \\
X_e
\end{bmatrix} = \begin{bmatrix}
Z_m & -K_f/H_{\text{close loop}} \\
H_{\text{close loop}} & K_p/H_{\text{close loop}}
\end{bmatrix} \times \begin{bmatrix}
X_h \\
F_e
\end{bmatrix}
\]  \hspace{1cm} (G.3)
G.2. Control architecture with interaction regulator

Figure G.2: The schematic of whole haptic teleoperation system with contact regulator. The strong gain ($P_{\text{strong}}$) is position gain when contacting with soft environment. The weak gain ($P_{\text{weak}}$) is position gain used in contact regulator mode. The switch block is

Compared with the simple position-force control architecture in late section, a force feedback is added to regulate contact force. However, the configuration at master side remains the same way. Hence, the equation of motion at master side can written as:

$$F_h = Z_m X_h - K_f F_e$$  \hspace{1cm} (G.4)

The configuration at slave side is modified due to introduce of force regulator. The displacement of slave robot is the position close response of system pulse the influence of regulator and environment force. Therefore, the equation of motion becomes:

$$X_e = H_{\text{close loop}} X_h - \frac{H_{\text{close loop}} F_e}{K_p} - \frac{H_{\text{close loop}} K_f F_e}{K_p}$$  \hspace{1cm} (G.5)

The H matrix can be expressed as:

$$\begin{bmatrix} F_h \\ -X_e \end{bmatrix} = \begin{bmatrix} Z_m & -K_f \\ H_{\text{close loop}} & -H_{\text{close loop}}(1 + K_f) \end{bmatrix} \begin{bmatrix} X_h \\ F_e \end{bmatrix}$$  \hspace{1cm} (G.6)

G.3. Identification of master device

As the master device has 3 degrees of freedom, the open loop response to chirp signal input shows a multi-degree motion. Hence, the transit acceleration response is used to estimate the inertia of master device in translational direction. An accelerator is mounted on device to measure the acceleration (see Fig.G.3).
G.3. Identification of master device

To minimize the external influence, the signal is an impulse signal with width of 0.05s. Signals with different amplitudes are used to derive the relation between actuation force and acceleration. By analysing the collected data shown in figure G.4, the inertia in translational direction can be estimated as 0.66 approximately. Additionally, based on the information in appendix E, the damping value is estimated as 0.07.

The transfer function of master device in translational direction can be estimated as:

$$H_m = \frac{1}{0.66s^2 + 0.07s} \quad \text{(G.7)}$$

Figure G.4: The impulses force input and measured acceleration. The up four plots describe accelerations when the input is impulse signal with four different amplitudes of 1.5, 2, 2.5 and 3N.