



Endstops for the Mechatronic Demonstrator

Albert Post

Individual Design Assignment

Supervisors:

prof.dr.ir. J. van Amerongen

dr.ir. J.F. Broenink

ir. M.A. Groothuis

A.P. de Vries

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Control Engineering

EE-Math-CS

University of Twente

P.O.Box 217

7500 AE Enschede

The Netherlands

Summary

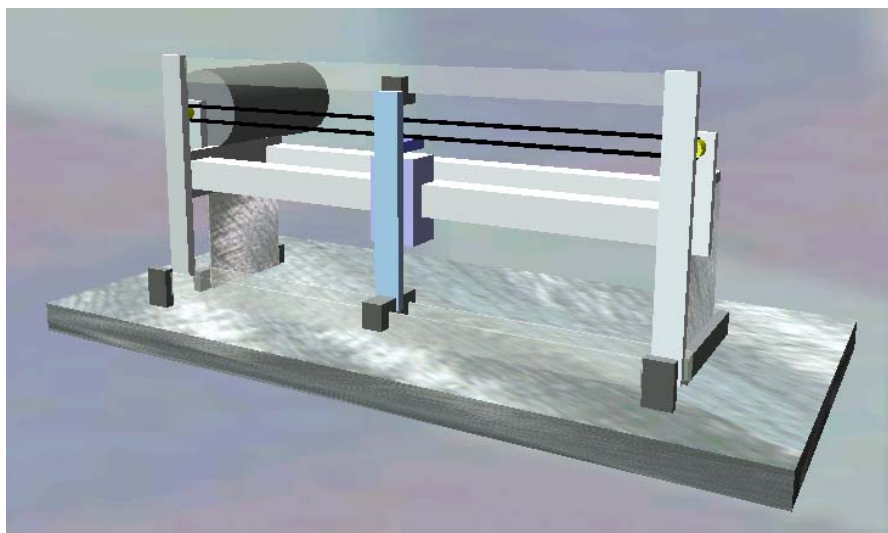
The mechatronic demonstrator is developed for students to learn the theoretical aspects of control engineering and to apply this theory in practice. The demonstrator is provided with a hardware safety layer for personal security and to prevent damage. The safety layer exists of two end switches which disable the motor amplifier, when the slider pushes a switch. This layer prevents that the motor damages the demonstrator. The old safety layer is not sufficient and the end stops have too little functionality.

In this individual design assignment an analysis has been done to solve the problems and improvements concerning the safety layer of the mechatronic demonstrator. Especially the end stop functionality of the demonstrator needs to be analyzed. Three items of the end stops have to be improved. The first item is the motor brake when an end stop is pushed. The second item is the direction dependency of the slider when an end stop is active. And the last imperfection is that the end stops do not support the homing of the slider.

These imperfections are improved and new functionality is implemented on a printed circuit board. The motor brake is improved with a TRIAC. The TRIAC short circuits the motor to decelerate faster instead of the previous disabling of the motor amplifier. Further, the end switches are now direction dependent, allowing the slider always to move away from the end switch. Furthermore the end stops are connected to the computer. With this end stop information a homing operation is added. This bachelor assignment has resulted in an increased end stop functionality of the mechatronic demonstrator.

Some recommendations are presented in this report:

- A software safety layer is recommended. This software prevents that the slider does not touch the end stops and so, it improves the solutions of some problems.
- Implement a slider velocity limiter in software. The slider velocity has to limit to approximately 1.5 m/s.
- Implement the detection of the marker in the homing operation, because this detection is currently not implemented in the homing operation. Furthermore, examine the efficiency of the homing speed.
- Change the current timing belt for a stronger one, and replace the pulleys for bearing pulleys to pre-tension the belt.



Samenvatting

De mechatronic demonstrator is een opstelling voor studenten om theoretische aspecten van de regeltechniek te leren en toe te passen in de praktijk. De demonstrator is voorzien van een hardwarematige veiligheidslaag voor persoonlijke veiligheid en ter voorkoming van schade aan de opstelling. De huidige beveiliging bestaat uit twee eindschakelaars die de motorversterker buiten werking stellen wanneer de slider een schakelaar aanraakt. Op deze manier wordt voorkomen dat de motor schade aan de opstelling toebrengt. De oude veiligheidslaag is niet voldoende en heeft te weinig functionaliteit.

In deze individuele onderzoeksopdracht is een analyse uitgevoerd naar problemen en verbeteringen met betrekking tot de veiligheidslaag van de mechatronic demonstrator en in het bijzonder de functionaliteit van de eindschakelaars. Drie aspecten van de schakelaars moeten verbeterd worden. Het eerste punt is het remmen van de motor wanneer een eindschakelaar is ingedrukt. Het tweede punt is richtingsafhankelijkheid van de slider, wanneer een eindschakelaar is geactiveerd. Het laatste punt is dat de eindschakelaars geen initialisatie van de slider positie ondersteunen (homing).

Bovenstaande punten zijn verbeterd en nieuwe functionaliteit is toegevoegd en gerealiseerd op een printplaat. Het remmen van de motor is verbeterd met behulp van een TRIAC. De TRIAC sluit de motor kort waardoor de deceleratie van de motor sneller wordt, in tegenstelling tot de vorige uitschakeling van de motor versterker. Verder is de richtingsafhankelijkheid van de slider geïmplementeerd. Hierdoor kan de slider zich altijd van de eindschakelaar verwijderen. Ook zijn de eindschakelaars op de computer aangesloten. Met behulp van deze data is een homing operatie gemaakt met 20SIM. De andere eindschakelaar functies zijn gerealiseerd op een printplaat. Dit onderzoek heeft uiteindelijk geleid tot verbetering van de functionaliteit van de eindschakelaars van de mechatronic demonstrator.

Enkele aanbevelingen komen naar voren in dit verslag:

- Een software veiligheidslaag wordt aanbevolen. De software voorkomt dat de slider de eindschakelaars aanraakt. Deze software verbetert de bestaande oplossing.
- Het implementeren van a snelheidsbegrenzer in software, zodat de slidersnelheid begrensd wordt op ongeveer 1,5 m/s.
- Toevoegen van de detectie van de marker in de homing. Deze functie zit nog niet in de bestaande homing functie. Verder kan de efficiency van homing snelheid onderzocht worden.
- Vervang de huidige tandriem voor een sterker exemplaar en vervang de pulley's voor gelagerde pulley's om de tandriem beter op spanning te kunnen brengen.

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1 Introduction

The aim of this Individual Design Assignment is to improve the functionality of the end stops of the Mechatronic Demonstrator. This chapter gives a short introduction on the mechatronic demonstrator. The function of the demonstrator and the current safety layer will be explained shortly. And last the problems with the requirements are mentioned.

1.1 Mechatronic Demonstrator

20-Sim is a software application for creation and simulation of dynamic models and control systems. One of the supported features is the ability to generate C-code of the model for a real time computer. These 'Mechatronic Demonstrator' setup is supposed to be used at lectures in Control Engineering in the Electrical Engineering and Mechatronics curriculum of the University of Twente. These Lectures contain theory of simulation of dynamic models and control systems. The objective of the demonstrator is to support that theory by examples in practice on a mechatronic device. Besides making the theory more insightful, real limitations in practical setups can be shown easily.

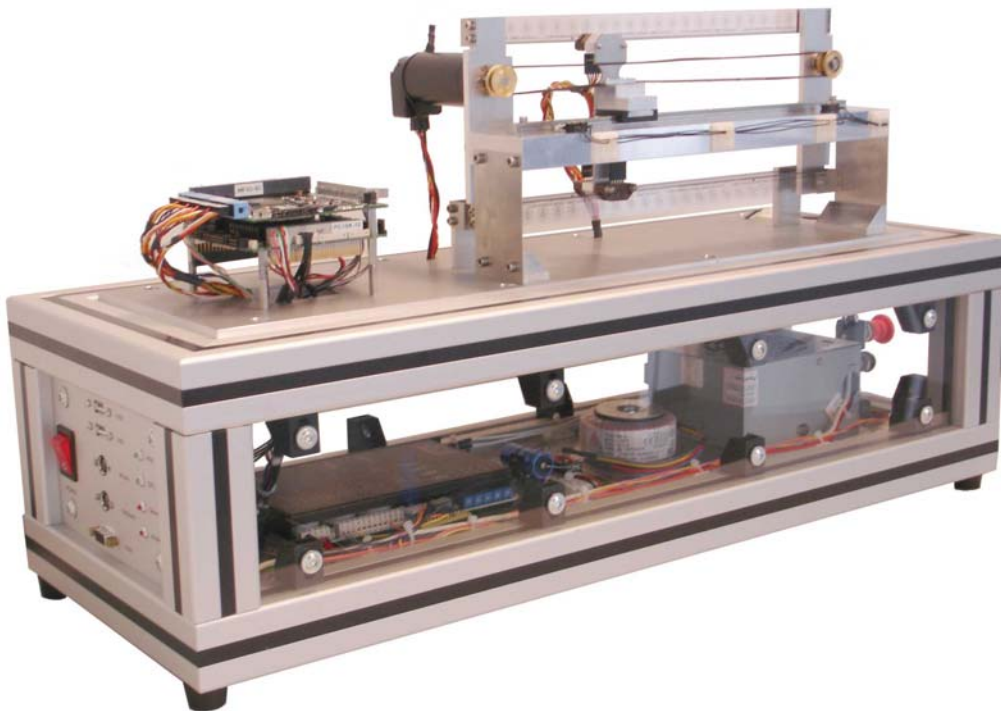


Figure 1 - The Mechatronic Demonstrator (Dirne, 2005)

The mechatronic demonstrator contains electronics and mechanics; a computer (PC/104) with an external IO-board (with a digital to analog converter) and a mechanical slider on a rail. A belt is used for the connection between motor and slider. The rail is connected via a special construction with two springs to the fixed world. Due to this flexible frame, the demonstrator is assumed to behave like a fourth order model which makes it interesting for educational purposes.

In 2003 the first mechatronic demonstrator was build by Controllab Products BV (Kleijn, 2003). Hans Dirne builds a second demonstrator. More information about this mechatronic demonstrator is reported by Dirne (2005). Figure 1 shows this demonstrator.

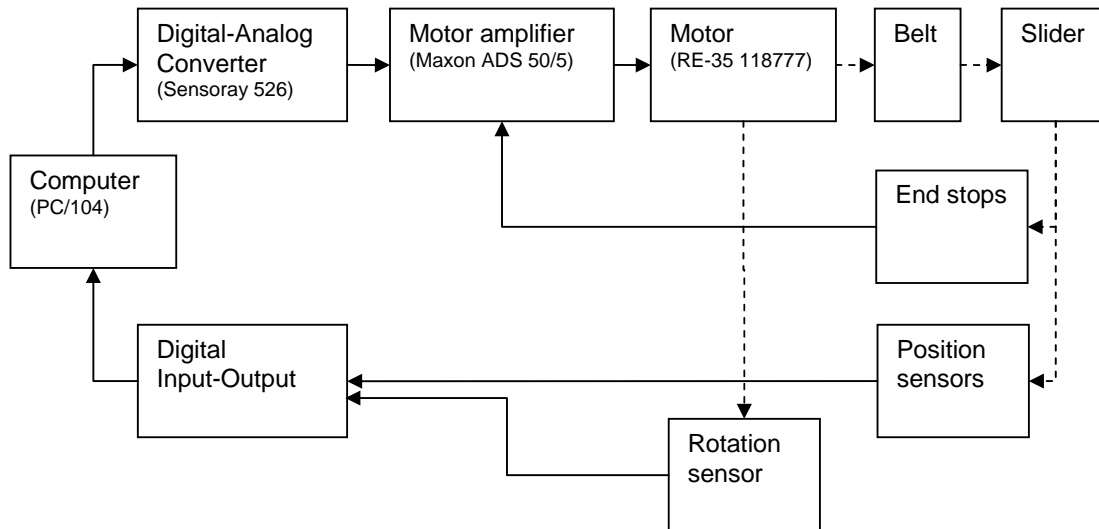


Figure 2 - Simple model of the demonstrator

1.2 Problem description

A hardware safety layer exists on the demonstrator. The safety layer prevents damage to the slider and motor when someone makes a mistake or the controller becomes unstable. The safety layer of the demonstrator consists of three switches: one emergency stop and two end stops mounted on the left and right end of the rail. The three switches disable the motor supply so the motor is switched off.

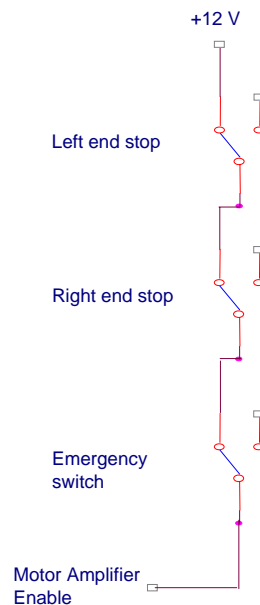


Figure 3 – Electric schematic of the end stops in the old situation

In Figure 3 the schematic of the old electronic circuit is displayed. This safety layer is simple and the functionality of the end stops is limited in this situation.

The problem can be divided in three sub problems:

1. The slider does not stop in time. The slider moves to the end of the rail, the switch is activated, but the slider bangs against the side and therefore sometimes the belt tears off, because the disabling of the motor amplifier is not sufficiently to brake the motor.
2. The end stop responds independently to the slider direction. When the slider activates the end stop, the motor power amplifier is disabled and so the controller cannot move the slider left or right. So the slider must be moved to the middle of the rail by hand and the motor power amplifier must be reset.
3. The computer does not know the start position of the slider at starting. The cause of this is that the position sensor only measures the relative displacement and not an absolute position. The computer needs to remember the place of the slider and have to calculate the position each time again. Comparable to the second problem, the slider must be moved to the middle of the rail by hand.

1.3 Objective

The objective of this individual design assignment is to solve the problems and to improve the functionality of the end stops. Research has to be done to create an overview of the current and alternative brake systems. Finally, the homing operation has to be renewed, so the computer can initialize the position of the slider.

Summarized, a demonstrator with improved safety layer has to be created, where it is *not* needed to remove the plastic cover and to move the slider manually.

1.4 Requirements

The new safety layer has to satisfy several requirements. This section presents the requirements.

- The safety layer has to stop the motor in case of an end switch or the emergency switch is pressed.
- The emergency stop should be fast enough so the demonstrator will not damage, or the safety layer has to prevent such situations.
- No need to move the slider manually in case of errors and for the homing operation. When this is realized, there is no need to remove the plastic cover anymore.
- The end stops are suitable to support the homing operation.
- The power amplifier (Maxon Servo amplifier DES 50/5) should be kept, because it is a special linear 'current' amplifier together with the digital-analog converter (Sensoray 526).

1.5 Outline of the report

In this chapter the mechatronic demonstrator is introduced. Some imperfections of the safety layer are seen. And so the functionality of the end stops of the demonstrator has to improve.

Chapter 2 describes the analysis of the demonstrator. This analysis is necessary to get an overview of the different parts of the demonstrator. A good knowledge of the hardware functionality is necessary to identify the problems and limitations of the safety layer. After this analysis several alternatives are given and discussed.

In chapter 3 the methods to improve the functionality of the end stops will be discussed. A new hardware design is introduced and the used components are explained.

The implementation and measurements of the safety layer are discussed in chapter 4.

And last the conclusions and recommendations are discussed in chapter 5.

2 Analysis of the functionality of the end stops

This chapter discusses the characteristics of the demonstrator and especially the end stop functionality. This analysis is necessary to get an overview of the used hardware. The characteristics will be analyzed to identify the problems and limitations. Several alternatives are discussed to get a realistic solution.

2.1 Characterization of the demonstrator

2.1.1 Characterization of the motor brake

In the old situation, there is only passive braking of the motor. When an end stop is pushed, the motor amplifier is switched off and that is all (see Figure 3). So the slider decelerates only by the friction of the slider and motor.

Next, the characteristics of the current motor without slider will follow. Three tests have been done to measure the stop time with different brake methods to stop the motor. In all three test cases the velocity of the motor is measured in revolutions per second as function of the time see Figure 4 and Figure 5.

The motor has in these tests a constant velocity of 88rev/s at $t = 0$. The brake action starts each time at t is 2 s. In the first test, the motor poles are short circuit; the motor voltage becomes 0V. In the other two tests the motor amplifier is configured as a current source. The second test shows the motor velocity with a switched set point from +1 to 0 Ampere (at $t=2s$). And in the last test the set point is changed from +1 A to -1 A (at $t = 2s$).

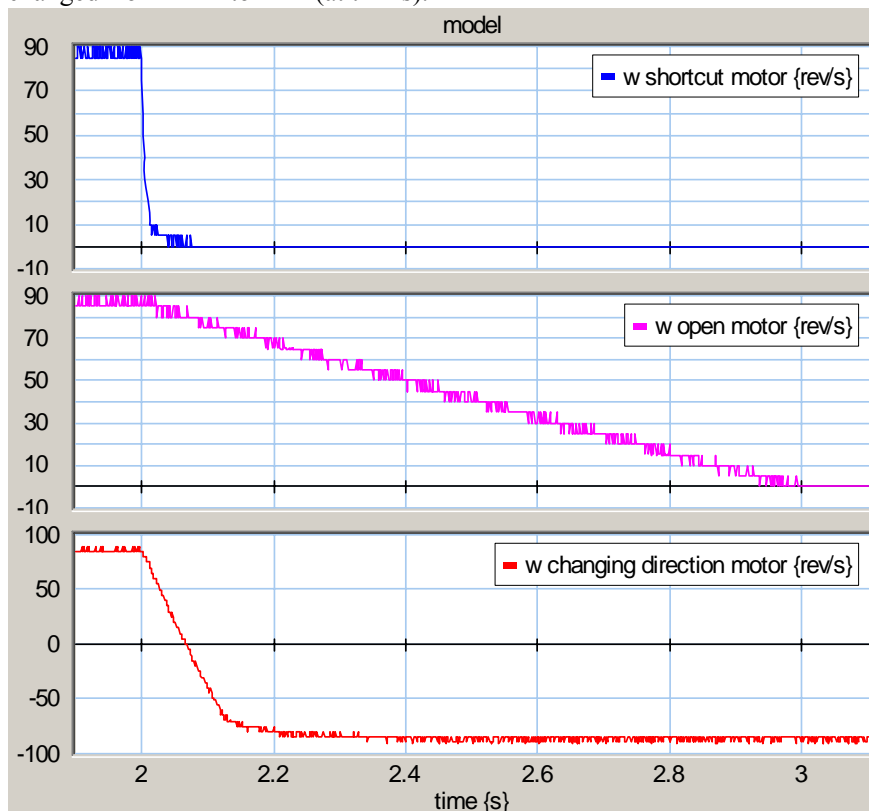


Figure 4 – Measurement of the motor velocity by 1) Short circuit motor; motor voltage is changed to 0V; 2) Open circuit motor; motor set point is changed from 1A to 0A; 3) Changing motor direction; motor set point is changed from +1 A to -1 A.

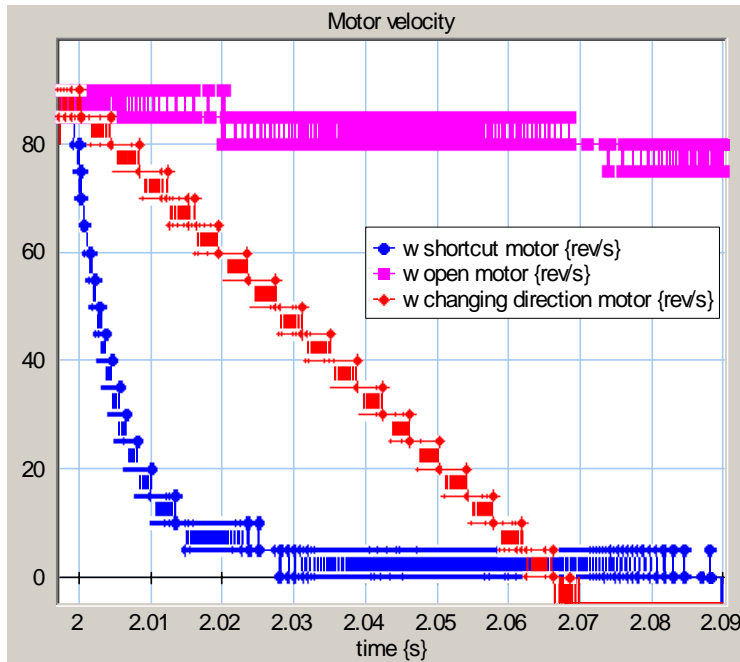


Figure 5 – Close up of the measurement of the motor velocity without slider by 1) Short circuit motor terminals; 2) Open circuit motor terminals; 3) Changing motor direction

In the first test the motor velocity decreases exponentially. This exponential behavior can be explained, because the motor voltage is regulated by the short circuit. The average deceleration of the motor is approximately 2000 rev/s^2 . The measurement was done without slider, but when this data is converted to translation, the slider should be decelerating 100 m/s^2 average.

In test 2 and 3 the motor deceleration is constant. Deceleration of test 2 is approximately 88 rev/s^2 . The slider decelerates theoretically 4 m/s^2 . In test 3 the deceleration is 1350 rev/s^2 and the slider deceleration is (theoretically): 66 m/s^2 . So, the bigger the deceleration, the shorter the brake distances.

See Table 1 for a summary.

Test #	Description	Measured Motor deceleration $\alpha \text{ [rev/s}^2\text{]}$	Theoretical slider deceleration $a = 2 \cdot \pi \cdot r \cdot \alpha \text{ [m/s}^2\text{]}$ with: $r = 7.76 \cdot 10^{-3} \text{ m}$
1.	Short circuit	2000	100
2.	Set point change: $1\text{A} \rightarrow 0\text{A}$	88	4
3.	Set point change: $1\text{A} \rightarrow -1\text{A}$	1350	66

Table 1 – Measurement results of the motor velocity by different motor brakes.

The start velocity of the motor is 88 rev/s in these measurements, this corresponds to a theoretical slider velocity of 4 m/s , but the slider can not move with this velocity in practice. This measurement is only been done to analyze the deceleration of the used motor with different voltage and current changes.

2.1.2 Characterization of the motor control

The currently used motor amplifier is the Maxon ADS 50/5. This motor power amplifier of the demonstrator can be configured in different ways: voltage-, current-, tacho- and encoder- control. The

first two controllers use the internal voltage and current sensors to control the motor. The last two configurations require an external tachometer or encoder sensor.

The sensors of the demonstrator are only connected to the computer and not to the motor amplifier, because the computer with sensors has to control the slider. So, only the voltage and current configurations of the amplifier are interesting. The amplifier has no explicit braking function, but when the amplifier is configured as a voltage source and the set point becomes 0 or negative, the motor velocity will decrease fast. This is possible because the motor amplifier is a four quadrant amplifier.

The current-torque relation is approximately linear (Maxon motor, datasheet) and therefore the power amplifier of the motor is configured as current source. When the current source is disabled or similar the set point becomes zero, the motor velocity will decrease linear and slowly (depending on its friction). If the set point of the current source is not zero, the motor will decelerate or accelerate with respect to the current. The maximum acceleration and deceleration are bounded by the current limiter.

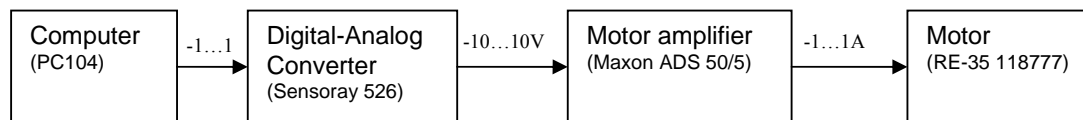


Figure 6 – Set point

The motor amplifier is controlled by the PC/104. This is the controller of the demonstrator. Because the set point input of the motor amplifier requires an analog signal, therefore between the amplifier and the PC/104 an analog-digital converter is present. The set point has a value between +10V and -10V this corresponds to a current of between +1 A and -1A. The current limiter of the motor amplifier has been set to 1A.

2.1.3 Characterization of the homing

The position of the slider is needed for a correct homing operation. Therefore, the available position sensors on the demonstrator have to be analyzed. There are three types of sensors: a linear strip with detector, end stops and a rotation encoder on the motor.

The strip with detector on the demonstrator measures relative displacement. These sensors are transmissive optical encoder modules. These are designed to detect linear relative displacement when used together with a linear strip. The strip also has a marker which can be used as a reference.

The rotation encoder measures relatively angular displacement.

When the slider hits an end stop, its position is known, but the controller is currently unable to detect the slider position or the end stop status.

2.2 Alternatives

This section discusses some alternatives to solve the problems, see section 1.2.

2.2.1 Motor brake alternatives

There are several possibilities to stop the motor. The analysis shows clearly that for slowing down the slider the current must be changed of direction or the motor has to be short circuited.

First the options will be explained.

1. A different motor amplifier for example an H-bridge with brake functionality. In the current configuration, the motor amplifier is configured as a current source. The current motor amplifier has no brake function.

Advantage	Disadvantage
<ul style="list-style-type: none"> - The new amplifier supports a brake function - Simple solution 	<ul style="list-style-type: none"> - Purchase costs of the new supply - Investment in the old motor supply is wasted - 20-sim models have to be changed - Current-Torque characteristic is less linear.

2. Using voltage control instead of current control. The motor brake is similar to short circuit the motor.

Advantage	Disadvantage
<ul style="list-style-type: none"> - No extra hardware is required; the current motor supply can be used. 	<ul style="list-style-type: none"> - Difficult modeling, because there is no linearity between voltage and torque. The current-torque characteristic is approximately linear and therefore it is used in the current demonstrator.

An extra option by 2 is to change the current control into voltage control only then, when an end stop is activated. So, no automation is possible, because the change of the configuration is made by dipswitches.

3. Change the set point. In this option the set point is changed by extra hardware or software when an end stop is active. The new set point value is negative to the old value and maximal so the motor stops fast.

Advantage	Disadvantage
<ul style="list-style-type: none"> - The current motor supply can be used, because this is a 4-quadrant motor control 	<ul style="list-style-type: none"> - Feedback of the velocity of the motor is required, because when the velocity of the slider reaches 0 m/s, the set point must be changed to 0A. - The maximum deceleration is proportional to the current, but the current is limited by the amplifier.

4. An extra circuit between the motor and the power supply. The function of this circuit is to short circuit the motor when an end stop is active. There are several solutions of this circuit to short circuit.

Advantage	Disadvantage
<ul style="list-style-type: none"> - The analysis has shown that the deceleration of the velocity is high. - The current motor supply can be used. 	<ul style="list-style-type: none"> - Requires an extra circuit with development costs and development time.

5. Mechanical brake. There are several solutions to stop the motor or the slider. For example fix some bumpers on the demonstrator to catch the slider. Or mount a Maxon motor brake on the motor. These options are extra; it can be implemented parallel to the electrical solution. And first the electrical solution is chosen.

When the solutions are compared, a short circuit is the best option. Because the deceleration of the motor is high and the current motor supply can be used in the same configuration (current-control). And also the 20SIM models do not need to be changed.

2.2.2 Short circuit alternatives

This section shows some alternatives to short circuit the motor. First the alternatives are described and one of them is chosen. The alternatives are: Relay, Solid State Relay (SSR), Mosfet and TRIAC.

- The relay is a simple method to short circuit the motor. The circuit is simple too, but there are a few disadvantages. The switch time of a relay is not so fast and this mechanical switching creates switch bouncing.
- The solid state relay (SSR) is a fast electronic switch, which is based on transistor technology. The lifetime of the SSR is higher than a relay, because that there are no moving parts, and thus no mechanical wear.
- A mosfet is a cheap and fast switching device. But the implementation is more difficult compared to using a relay.
- The TRIAC, or triode for alternating current, is a bidirectional electronic switch. The low power type is used in many domestic appliances. Triacs are obtainable in different versions and different power versions. It is also based on transistor technology and therefore fast switching. Triacs are available for very high currents and voltages.

Here the possible solutions in a table are:

Alternatives	Advantage	Disadvantage	Conclusion
Relays	Straightforward circuit	Slow switching Switch bouncing	+
Solid State Relays	Straightforward circuit Fast switching	High current SSR is not so cheap.	++
Mosfet	Fast switching Cheap	Difficult circuit and implementation	+/-
TRIAC	Fast switching Cheap High current and voltage Straightforward circuit		+++

Table 2 - Alternatives for the motor short circuit

The best and cheapest method to short circuit the motor is the TRIAC. The TRIAC can switch high currents and there is no difficult development.

2.2.3 Direction sensor alternatives

A sub problem is that the motor amplifier becomes disabled independent of the movement direction of the slider when it hits one of the end stops. It is desirable that the motor amplifier is enabled when the set point changes in such way that the slider moves back. Some alternatives for direction sensors will be described.

- One solution is that the software driver converts the ‘analog signal’ to a digital signal which contains the direction information and sends this calculated value to a digital output port.
- The other solution is to use a voltage comparator. The detecting of the motor direction can be measured by the set point. The set point has an analog value between -10...10V generated by the digital to analog converter (Sensoray 526). A voltage comparator can translate this analog voltage to a digital value.

The hardware solution is chosen, because in the case of a software crash the hardware can stop the motor.

2.2.4 Homing alternatives

For the homing problem, three alternatives are discussed:

- An alternative is to change the position sensor strip for another strip which contains absolute position indication. For this solution it is necessary to adjust the sensors and decoders. With this solution a homing operation is no longer needed, because the controller always knows the absolute position of the slider.
- Connect the end stops to the PC/104. The current position strip contains a marker at a fixed position. The controller can move the slider to the marker with the help of the end stops. So the controller can calculate the position of the slider with the marker position or with the end stop positions.
- It is not per se necessary to connect the end stops to the computer. The computer can detect the end stops with the position detectors and without the end stop status signals. With this relative position information the computer can calculate the velocity and the acceleration. These data together with the output current, give the end stop information. For example when the slider is activating an end stop the velocity and the acceleration of the slider become zero. The computer can detect an end stop when the set point of the current is not equal to 0 Ampere and simultaneously the velocity is 0 m/s and the acceleration is 0 m/s².

The last alternative is not so simple to implement in software, because double differentiation of the position is required to calculate the acceleration. And digital differentiation needs filtering to remove the noise. Furthermore the end stop information is not immediately available, because the deceleration of the slider needs to be calculated.

The connection of the end stops to the pc is in any case a good idea and the position strip with marker is already available on the demonstrator. So, the second solution is chosen. Therefore the end stops have to be connected to the computer. The status of the end stop can then be used for the homing operation.

2.3 Additional restrictions

This section analyzes some additional restrictions. The deceleration and velocity of the slider are related. The faster the slider moves, the bigger the deceleration to keep constant the stop distance of the slider. This section discusses these parameters. The used calculations are discussed in Appendix H.

2.3.1 Maximum deceleration

The deceleration and the force have a linear relation. The force is limited by the weakest link. For the timing belt a maximal tension of 7 Newton is specified by the manufacturer. The manufacturer of the rail has specified a maximal acceleration of 80 m/s². This corresponds with a force of 9.52 N (The mass of the slider is 119 gram).

So, the maximal brake force is limited by the timing belt (7 Newton). This corresponds to a maximal deceleration of ~58m/s².

2.3.2 Maximum current

The conversion of the voltage to the current of the power amplifier is established as 0.1 A/V (Dirne, 2005). This establishment is configured by the current limiter of the amplifier. Therefore, the current of the motor amplifier is limited to 1 Ampere. So, the maximal acceleration or deceleration of the slider controlled by the amplifier is theoretical 42 m/s², Appendix H discusses this calculation.

2.3.3 Maximum velocity

The velocity has to be limited because the deceleration is limited. Some alternatives to limit the velocity are discussed in Appendix A. This appendix discusses four possibilities to realize the velocity limiting in hardware, but no hardware solution serve the purpose. Therefore in the final realizations of

the PCB no velocity restriction is present. A recommendation is to implement a velocity limiter in the controller software.

2.3.4 Maximum stop distance

The slider needs some distance to decelerate. The faster the deceleration gets the shorter the needed stop distance. The maximal available distance between the end stop and the end of the rail is approximately 3 cm. The slider length is also approximately 3cm. When the stop distance becomes bigger the free space of the slider is proportionally smaller. Thus the slider has to stop within 3 cm without touching the side.

2.4 Conclusion

From the analysis of the demonstrator, it has become clear that the end stops have to be improved. When the slider activates an end stop, the slider does not brake, but only the motor power amplifier is disabled. So, the deceleration of the slider is insufficient. Furthermore, it is necessary that the maximum speed of the slider is not too high, because the deceleration is limited. A speed limitation will not be implemented in hardware. Furthermore from the analysis, it has become clear that the brake force of the motor is limited by the current limiter of the motor amplifier, because of this the slider can not decelerate fast enough. Necessarily a brake function has to be implemented. The chosen method is to use a TRIAC to short circuit the motor. Further to determine the direction of the slider, a voltage comparator is chosen to convert the analog set point.

The methods of the chosen items are described in chapter 3.

3 Method to improve the end stop functionality

This chapter discusses the methods to improve the end stop functionality and how these can be realized. First, the different methods are discussed. Further a block diagram is introduced to make the different parts understandable. At the end of this chapter a final electric schematic for every part is discussed.

3.1 Chosen methods

3.1.1 Brake method

This section describes the brake method. The main component to brake the motor is the TRIAC. This component is chosen in the previous chapter. The TRIAC, or TRIode for Alternating Current is an electronic component and exists of N- and P-material, just like a transistor, but with an different structure. The TRIAC is a bidirectional electronic switch which can conduct current in either direction when it is enabled. It is enabled by a voltage, which is applied to its gate electrode. The used TRIAC is displayed in Figure 7.

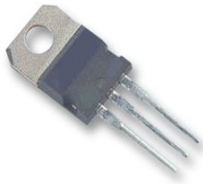


Figure 7 – TRIAC; BTA08-600BRG TO-220AB

The chosen type is the Triac BTA08-600BRG, this is an 8A 600V TRIAC, with a current peak of 80A. It is chosen arbitrary; however the current and voltage of this type are enough.

3.1.2 Direction dependency method

The chosen method for the direction problem is to use a voltage comparator to get the direction information from the set point. The comparator converts the analog value of the set point into a digital value (1 or 0). This value corresponds to the direction of the slider (left or right). So, the voltage comparator seems to be a Sign function. The voltage comparator should have a high impedance input, so the Sensoray 526 (DAC) is not overloaded. The Sensoray has an analog output with a range of -10...10V and 2mA output. The chosen voltage comparator is the LM311.

3.1.3 Homing method

The homing operation initializes the controller with the absolute position information of the slider. It is a moving operation of the slider to a reference point. The reference point consists of a marker on the linear encoder strip. The detector detects the marker and gives feedback to the controller. The marker has the same precision as the resolution of the linear strip and the position sensor: 40,000 ticks/m this means an accuracy of 25 μ m.

The implementation of the homing is simple; a move action to the left end stop and a move action to the right to detect the marker or to calculate the center.

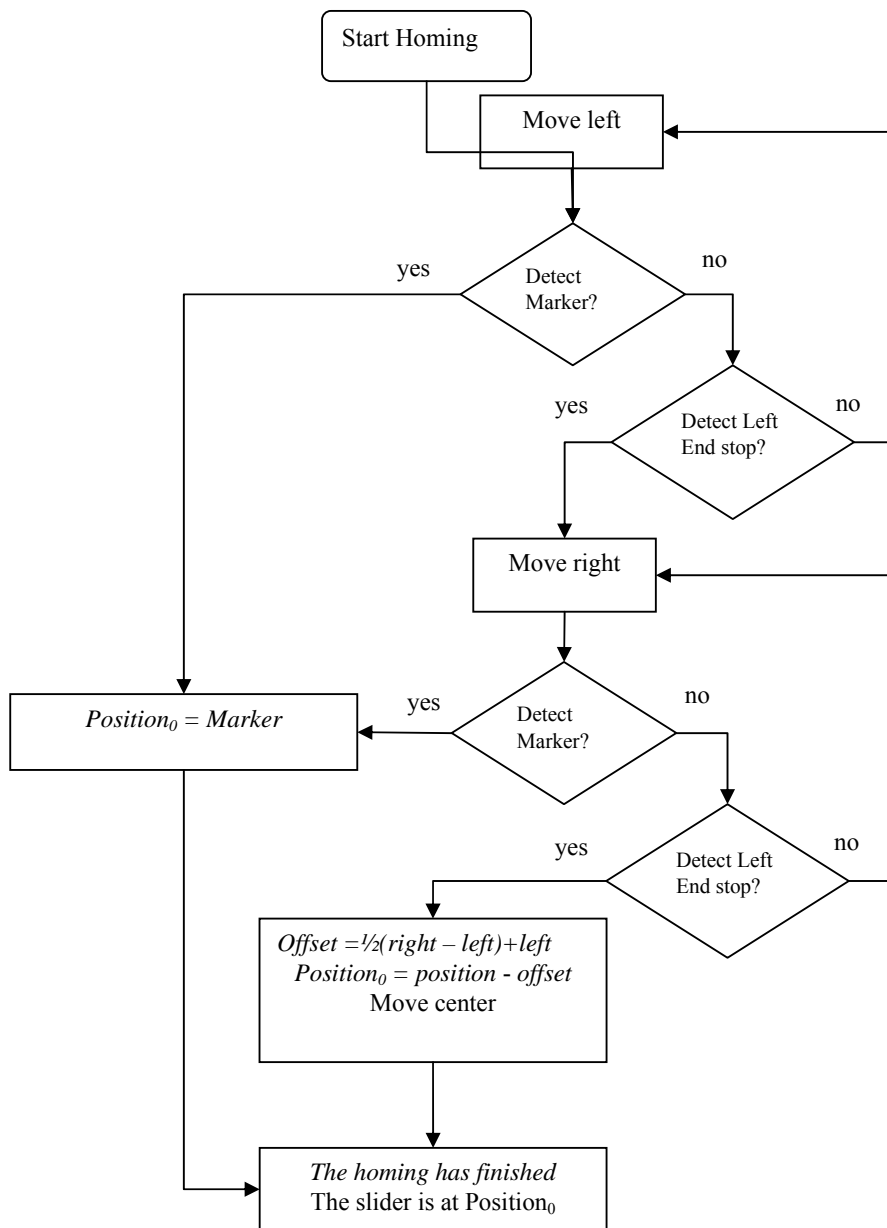


Figure 8 – Homing operation

The offset of the marker to the middle of the rail can be calculated to initialize the position at 0 when the slider is in the middle between the end stops.

3.2 Block diagram

Figure 9 shows a block diagram of the wanted end switch implementation. Two parts of the block diagram are obviously the motor and the power amplifier. The motor amplifier is the current source for the motor.

Further the block diagram contains a short circuit block. This short circuit block is inserted to connect the two terminals of the motor together with a low resistant conductor when the motor amplifier is disabled. So when an end stop is activated, the amplifier has to be disabled and the motor has to be short circuit.

The brake function of the slider has to be direction dependent. This means that the slider has to be brake if and only if the end stop is activated and the slider moves in the wrong direction (in the direction of the end of the rail). The enable signal has to be a function of the direction of the slider.

The objective is that the motor only brakes when an end stop is touched and the orientation of the set point is 'wrong'. When the set point orientation is 'good', the slider has not to be brake even if the end stop is touched, so the slider can leave the end stop. This part in the block diagram has the following inputs: the two end stops and the direction information from the set point, the output is the enable signal for the motor brake.

This block diagram contains a logic block, a direction detector block and a motor brake block.

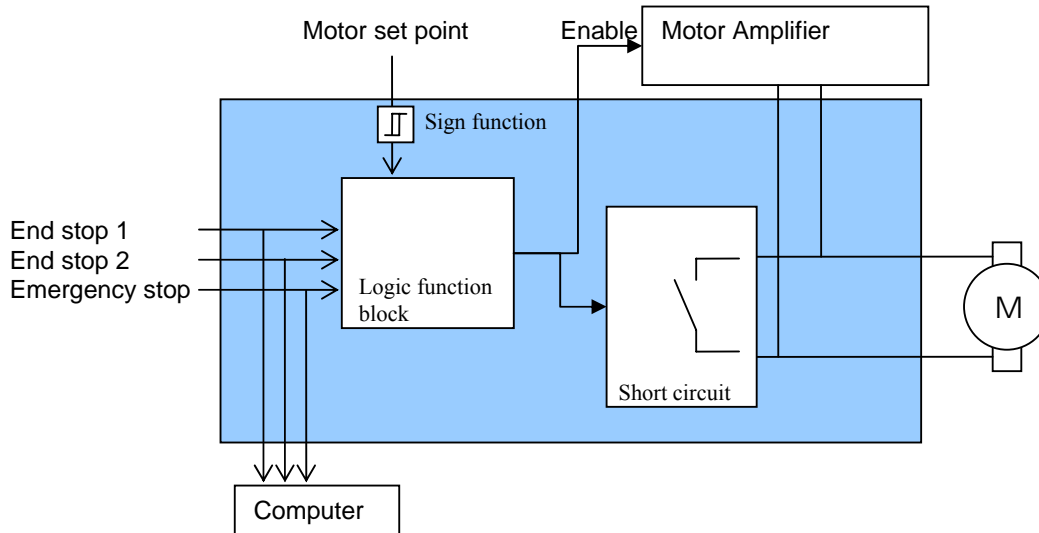


Figure 9 - Block diagram of the hardware safety layer

3.3 Electric circuits

This section explains the electric circuits that implement the functionality from Figure 9. See Appendix C for all schematics and see Appendix B for more information about the configuration of the hardware connectors.

3.3.1 Electric circuit of the motor brake

The TRIAC needs some other components to function properly. This section explains the schematics.

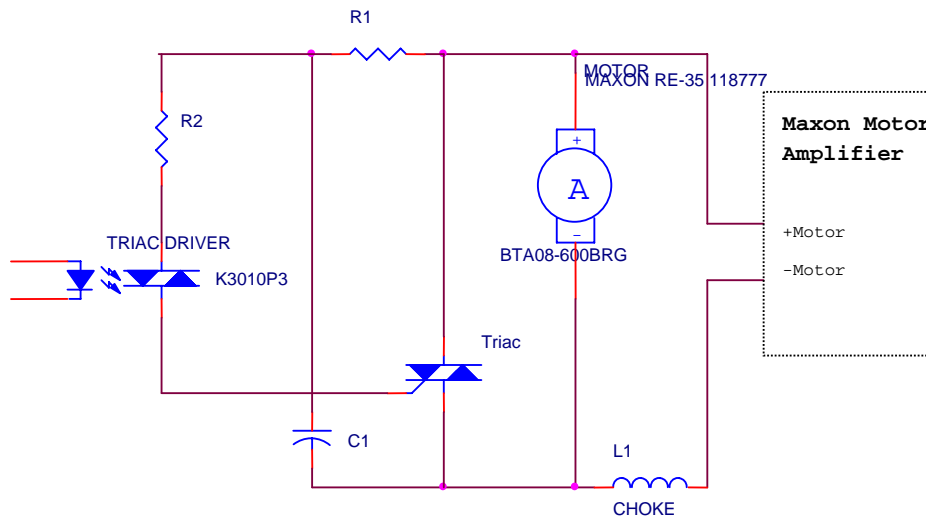


Figure 10 - Triac circuit

Figure 10 shows the electric motor brake circuit with the TRIAC. The TRIAC is controlled by a TRIAC driver. The TRIAC driver provides an optic isolation between the digital electronics and the TRIAC. The resistor R1 and the capacitor C1 build a snubber network. A snubber network is a resistor

and capacitor in series and is placed in parallel with the output of the TRIAC. The snubber network is needed because the motor causes noise. The resistor R2 regulates and limits the current into the gate. The TRIAC can short circuit the motor fast and independently of the motor polarity.

A choke is added to the motor circuit, according to the datasheet of the Maxon motor amplifier (Maxon motor amplifier, datasheet) an extra choke is necessary if the DC-motor has a terminal inductance lower than 0.35mH. The currently used motor has a terminal inductance of 0.34mH. A choke of 120 μ H is added. A choke is added instead of an inductor, because an inductor stores energy and the choke dissipates energy for higher frequencies.

3.3.2 Electric circuit of the direction dependency

This section discusses the electric circuits concerning the direction dependency. Three schematics are shown: the voltage comparator, the power supply schematic and the logic schematic.

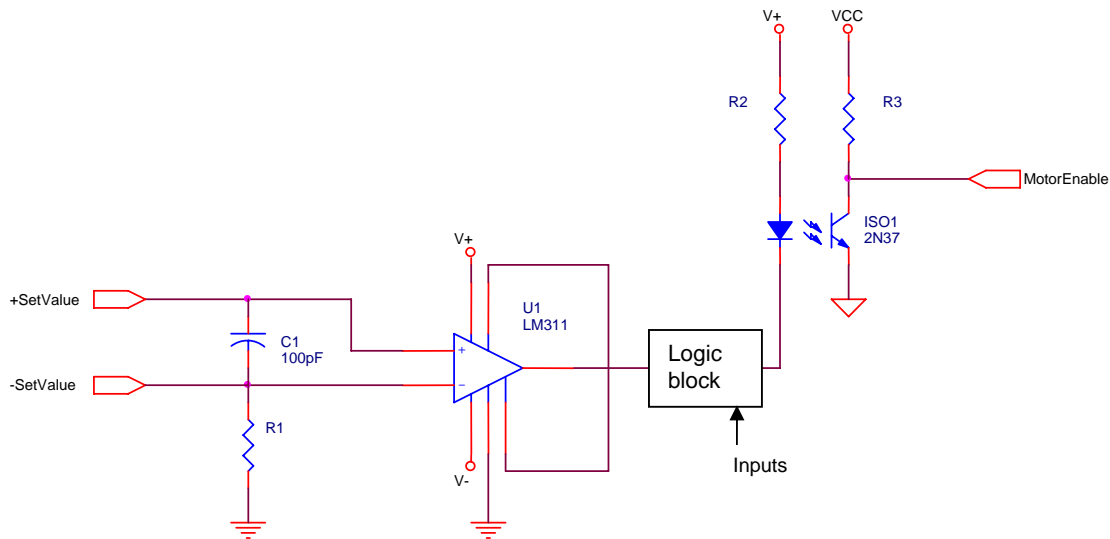


Figure 11 – Motor direction detector. The voltage comparator converts the analog voltage to a digital signal.

In Figure 11 the voltage comparator is shown. Dependent on the set point the output voltage is high or low. The optocoupler is added for galvanic isolation between the output and the motor amplifier. The right side of the optocoupler is connected to the motor amplifier together with its power and ground. In the schematic different symbols are used.

The comparator needs a positive and a negative power supply which have to be higher than its input range. The necessary voltages for this comparator are generated by a DCDC-converter. The chosen DCDC-converter is the IA0512S; it generates +12V and -12V from the 5V. A DCDC-converter is needed because only 5V is available on the print. The V+ and V- in the schematic are generated by the DCDC-converter.

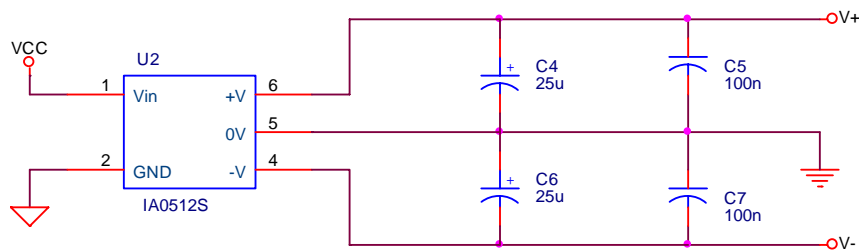


Figure 12 – DCDC-converter. It creates a +12V and -12V for the voltage comparator.

In Figure 12 the electric schematic of the DCDC-converter is shown.

Further, logic components are needed to create a function of the inputs to get the desired output. The inputs exist of two end stops, the emergency stop and the motor direction signal. The function can simply be written:

$$\text{MotorBrake} = \text{EndStopLeft} \cdot \overline{\text{Direction}} + \text{EndStopRight} \cdot \text{Direction} + \text{EmergencyStop}$$

There are several solutions to implement this function in hardware. One possibility is to use programmable logic, but the function is small and fixed. So, another method is chosen using standard gates. The function can be implemented with one Nand-IC and one Not-IC.

The components are:

Nand-gate 7400;

Not-gate: 7414.

The function of the logic is to give a brake signal dependent on the inputs: the end stops and the motor direction. The logic is fast enough, so the reaction time is not a bottleneck.

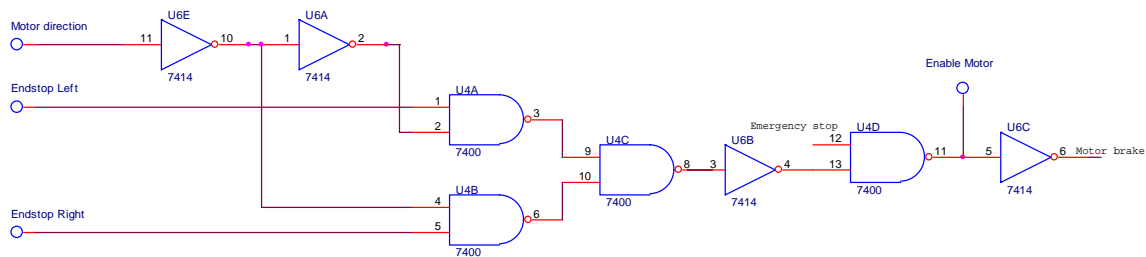


Figure 13 - Logic circuit

Figure 13 shows the realized circuit with a NAND and NOT gate. The end stops and the emergency switch are switches that are connected in normally closed mode. This means that the functionality of a not connected switch equals a pressed switch.

Some LEDs are added to the schematic for extra functionality. Two LEDs show the status of the switch and two other LEDs, red and green, indicate the motor direction. Furthermore, these LEDs indicate if the print is active and the power is turned on.

3.3.3 Electric circuit of the end stops

A debounce circuit is added between the end switches and the computer. The emergency stop and the two end stops are connected to the computer. More precisely, the switches are connected to the digital IO connector of the Sensoray IO-board. The debounce circuit is added to remove the contact bounce because contact bounce is a problem of mechanical switches.

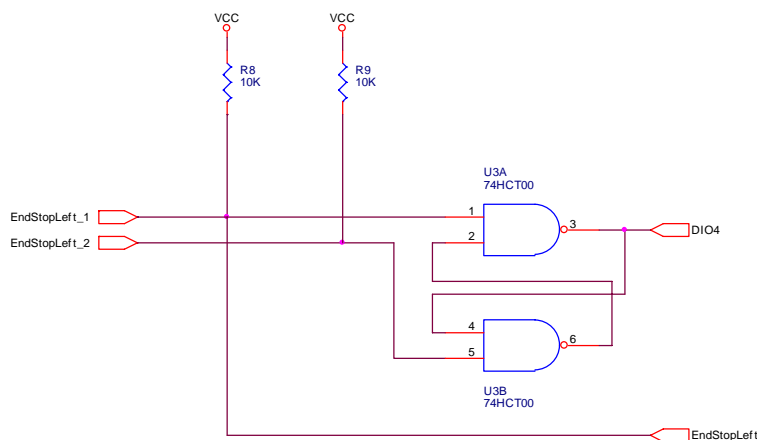


Figure 14 – Debounce circuit for the end stops

In Figure 14 the debounce circuit is shown. The end stop is connected to DIO-4 (this is a digital input output pin number) of the Sensoray board. The complete configuration of the connectors is described in Appendix F.

3.3.4 Electric circuit of the initialization

In the circuit with the start and emergency stop, a D-flip-flop is added to hold the enable signal. The start and emergency are respectively the set and reset. The resistor and capacitor create a reset on startup, because when the main power to the demonstrator is turned on, the amplifier and the motor have to be disabled to prevent unwanted movements.

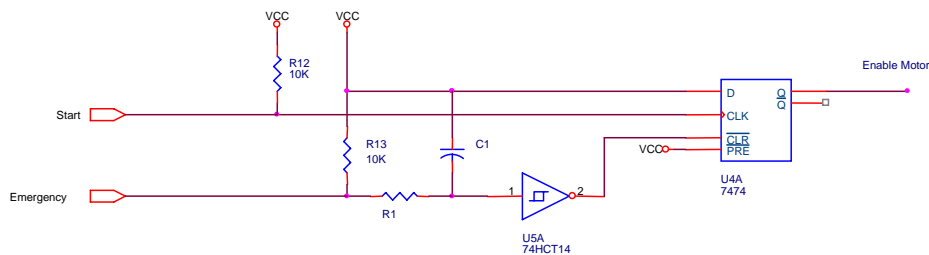


Figure 15 - Initialization circuit

3.4 Conclusion

In this chapter the chosen methods to improve the mechatronic demonstrator are described. These methods are used to realize the new functionality of the end stops. First the method to create an active motor brake with a TRIAC is discussed. Further the method to realize direction dependency of the slider is discussed and last the end stops connection to the IO-board of the computer is discussed. All method descriptions are equipped with the electric schematics. The next chapter handles the implementation and realization of these methods.

4 Realization and testing

This chapter discusses the realization and testing of the new functionality of the end stops. First a short preparation of the implementation is discussed. Then the realization is discussed. Furthermore the test cases of the test procedure are described and the results are shown. Finally, the validation of the results with the objective is done.

4.1 Preparation

Before the rest of this chapter, a short preparation is described of the first trail run. The printed circuit board is created and the connectors have to be connected. The left and right end stop can be mistaken, but this is depending to the connected + and – poles of the set point. It is recommend to remove the slider in the first trail run and to check if the polarity of the set point is matching with the two connected end stops.

After the right installation the end stops appeared to work properly. Take care of the timing belt, because in the case of an extremely braking force of the motor, the teeth of the belt are destroyed. So, it is recommended that a stronger timing belt is used and also replace the pulleys into bearing ones to pre-tension of the timing belt.

4.2 Realization

For a stable and robust realization of the hardware safety layer, the final circuit is made on a printed circuit board. The different circuits, described in chapter 3, are created on a single print. The specific information about the printed circuit board is discussed in the appendixes.

4.2.1 Power supply

The required voltage of the print is 5 Volt. The print uses approximately 100mA and so simply the 5V computer supply that is present on the demonstrator is used.

4.2.2 Printed circuit board details

All schematics of the electric circuits that are made are added in Appendix C – Printed circuit board schematics. The next appendix shows visually the connections between the PCB and the mechatronic demonstrator. See Appendix D – Printed Circuit Board Configuration.

For a detailed description of the used components and the used connectors, the next two appendices are added. Appendix E – Part list printed circuit board, this appendix presents the tables with the resistors, capacitors and other used components. And Appendix F – Connectors user manual explains the connectors of the PCB. The pin layout of each connector is described.

4.3 Test procedure

This section describes the functional tests cases of the PCB. The results of these test cases are described in section 4.4.

4.3.1 Motor brake test

Simple motor brake test

Action	Expected result
Start the slider with a constant velocity of 0.5 m/s.	<ul style="list-style-type: none"> The slider moves with a velocity of 0.5 m/s.
The slider activates a switch.	<ul style="list-style-type: none"> The motor amplifier is disabled. The slider brakes.

Deceleration of the slider

In this test case the deceleration of the slider for different slider velocities will be measured. 20SIM is used to steer the motor to move the slider with a defined velocity as far as the end stop and measure the velocity of the slider during this experiment. Further calculate the deceleration of these velocities.

Action	Expected result
Move the slider with a velocity v_n to the switch. $v_n = \{0.3 \dots 1.5\}$ m/s step 0.1 m/s	<ul style="list-style-type: none"> The switch is activated and the slider stops.
	<ul style="list-style-type: none"> Measurement results are available to plot graphs.

4.3.2 Slider direction test

Left end stop

In this test the direction dependency of the slider is tested. When the direction of the set point has changed from left to right or reverse, while the slider is pressing an end stop, the motor amplifier is not more disabled. So, the slider can leave the switch.

Check the functionality of the direction LEDs on the PCB.

Precondition	
The slider is pressing the left end stop.	
Action	Expected result
Change the set point slowly from: (left) to 0 to (right).	<ul style="list-style-type: none"> The slider moves to the right side. The direction LED 'left' is turned off and the LED 'right' is turned on.
Stop the test	<ul style="list-style-type: none">

Right end stop

Repeat the previous test for the right end stop.

4.3.3 Slider homing test

In this test the following aspects are measured:

- The status information of the right end stop is available on the controller.
- The status information of the left end stop is available on the controller.

The PC/104 controls the movement of the slider.

Action	Expected result
Move the slider to the left.	<ul style="list-style-type: none"> The slider moves to left. The slider activates the left end stop. The status information of the left end stop has changed to "active" on the controller. The left position of the slider is saved.
Move the slider to the right.	<ul style="list-style-type: none"> The slider moves right. The slider activates the right end stop. The status information of the right end stop is available on the controller. The controller calculates the distance between the end stops.
Move the slider to the center	<ul style="list-style-type: none"> Calculate the center of the rail. Move the slider to the center.
Optional	
The position detector detects the marker in one of above sequences.	<ul style="list-style-type: none"> The slider uses the fixed marker as reference. The slider moves to the marker.

4.3.4 Other tests

Power consumption

Action	Expected result
Connect the PCB to a 5 V power supply together with a current meter.	<ul style="list-style-type: none"> The PCB is ready and one direction LED is on.

Measure the current consumption of the PCB.	<ul style="list-style-type: none"> The current is 100 mA or less.
---	--

Status LED “Server Online”

Test the “Server Online” LED.

Action	Expected result
Switch on the “Server Online” LED.	<ul style="list-style-type: none"> The “Server Online” LED is on.
Switch off the “Server Online” LED.	<ul style="list-style-type: none"> The “Server Online” LED is off.

Status LED “Model Started”

Test the “Model Started” LED.

Action	Expected result
Switch on the “Model Started” LED.	<ul style="list-style-type: none"> The “Model Started” LED is on.
Switch off the “Model Started” LED.	<ul style="list-style-type: none"> The “Model Started” LED is off.

Status amplifier enabled

Action	Expected result
Press the start button	<ul style="list-style-type: none"> The amplifier is enabled. This status information is available in 20Sim controller.
Press the emergency button	<ul style="list-style-type: none"> The amplifier is disabled. This status information is available in 20Sim controller.

Start the demonstrator

Action	Expected result
Switch on the power of the demonstrator.	<ul style="list-style-type: none"> The PCB set the amplifier in disable mode.
Press the start button.	<ul style="list-style-type: none"> The amplifier is enabled.

4.4 Results

This section discusses some measurements of the final print. The different test cases in the previous section have to be executed and the measurements have to be shown.

4.4.1 Increasing deceleration

In the first test the stop distance of the slider was measured with different velocities. This measurement data is shown in Figure 16 and Figure 17.

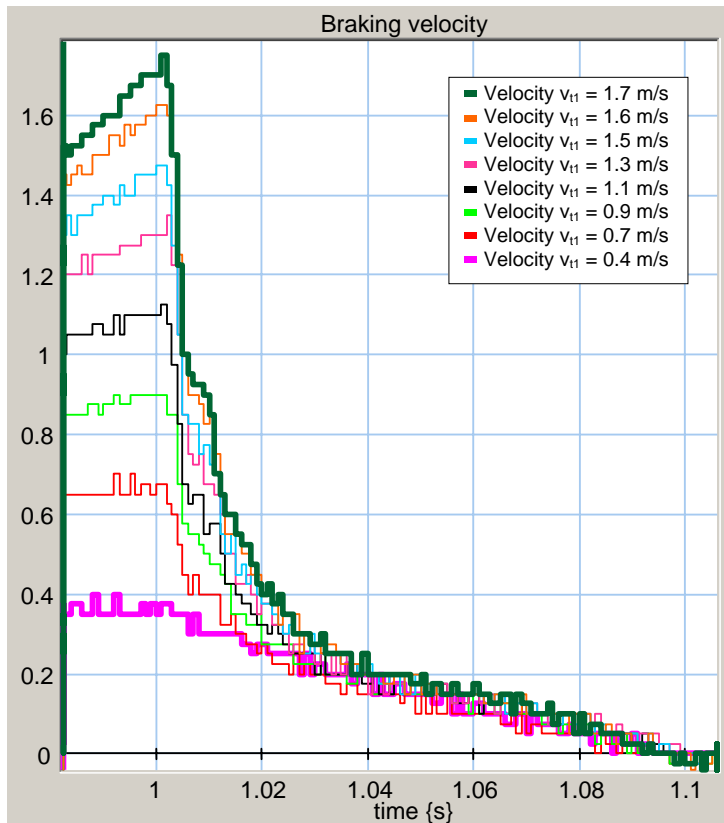


Figure 16 – Braking velocities $v(t)$ {m/s}. Different velocities are measured, when the end stop is pushed at $t=1$ s the slider brakes and the velocity decreases to zero.

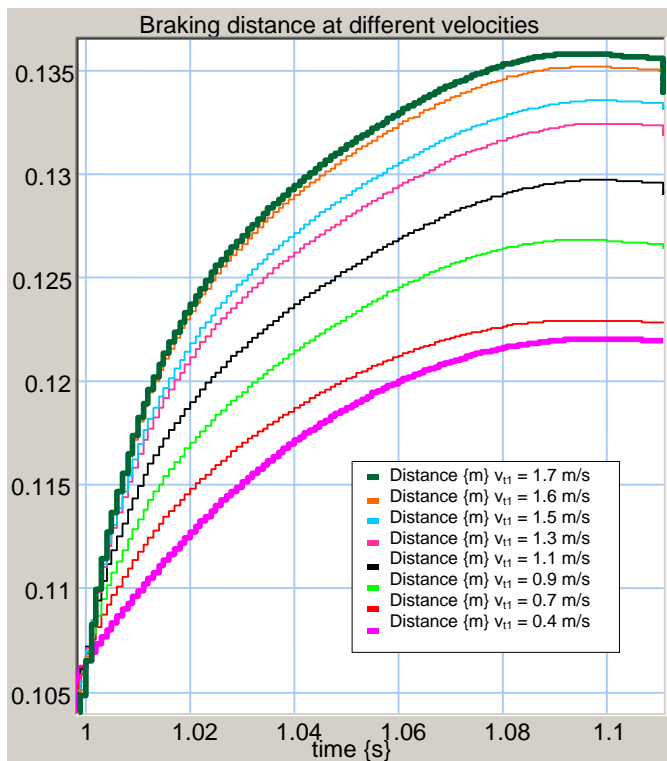


Figure 17 – Braking distances $x(t)$ {meter}. The position of the slider is measured with different velocities and the end stop is located at position $x=0.105$ m. The matching velocities are shown in Figure 16.

In Figure 16 the stop distance of the slider is shown. The stop distance is longer, when the velocity is higher.

When the slider moves more than 3cm, the switch is passed, because the size of the slider is 3cm. So, the velocity of the slider has to be limited at maximal 1.5m/s. The force of the motor is passed on the slider by the belt. In Figure 17 the different braking distances are shown for the specific test velocities. The end stop is pushed at $t=1s$. The velocities do not decrease linear, because the brake force is not constant, because the matching current is not constant, but dependent on the decreasing voltage of the motor.

Test #	Start velocity v {m/s}	Braking distance {cm}	Average deceleration {m/s ² } $a = \frac{1}{2} \frac{v^2}{s}$
1	1.7	3.1	47
2	1.6	3.0	43
3	1.5	2.8	40
4	1.3	2.7	31
5	1.1	2.5	24
6	0.9	2.2	18
7	0.7	1.8	14
8	0.4	1.7	5

Table 3 – Measurement results of the braking test

Table 3 shows a survey of the measurement results. It is clear that the braking distance gets bigger when the velocity gets higher. Also the average deceleration gets higher, but the stop distance is not smaller or stays constant, but the distance becomes longer. The deceleration of test 8: 5 m/s^2 is approximately equal to 4 m/s^2 which is the measured deceleration of section 2.1.1 with no braking functionality. So, with low slider velocities the short circuit does not increase the deceleration.

The short circuit method works, but insufficient. When an end stop is activated, the motor is short circuit and it stops. But the stop distance of the slider is dependently on the velocity. When the velocity is too high, the slider bangs to the side. Therefore the velocity has to be limited. So, a velocity limiter is recommended.

4.4.2 Direction dependency

The motor amplifier is disabled only dependently on the slider direction in combination with an end stop. When an end stop is activated the motor supply is disabled, but when the set point is changed, the motor direction becomes negative to the previous direction (previous set point), and then the motor supply is enabled and the slider can leave the end stop. So the software has to change the set point and is able to drive the slider. In the next section it is shown that the direction dependency works properly.

4.4.3 End stop connection to the computer

The end stops are connected to the computer. So, it is possible to check the state of the end stops and do a homing operation.

In 20SIM a simple homing operation with end stops is added to an existing 20SIM model.

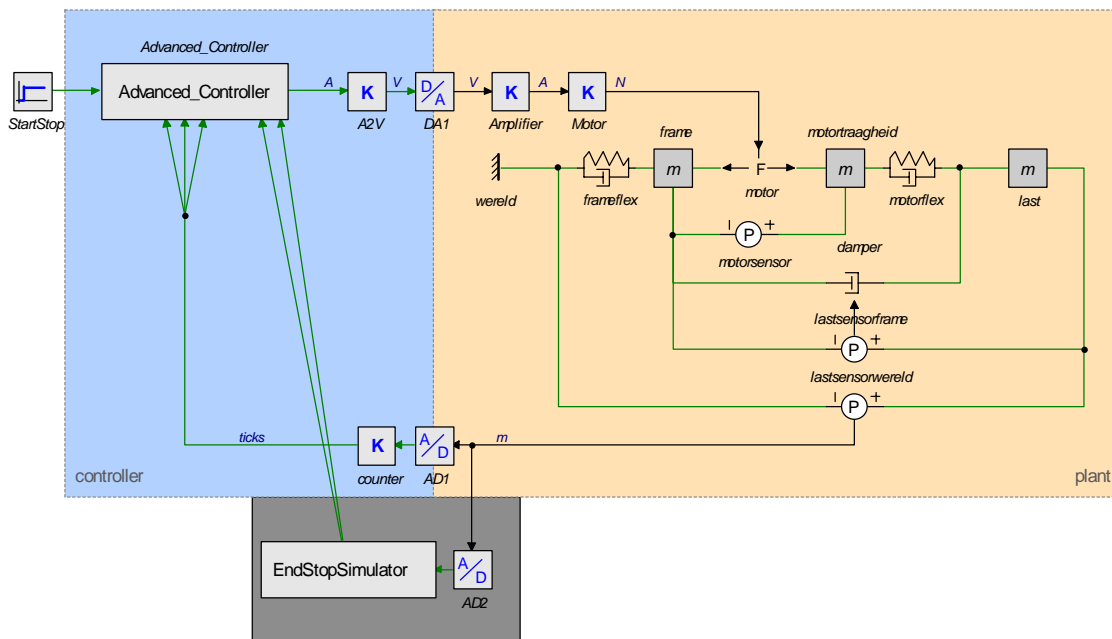


Figure 18 – 20SIM model of the Mechatronic Demonstrator with homing functionality

In Figure 18 the 20SIM model is shown. The EndStopSimulator sub model and the AdvancedController are added.

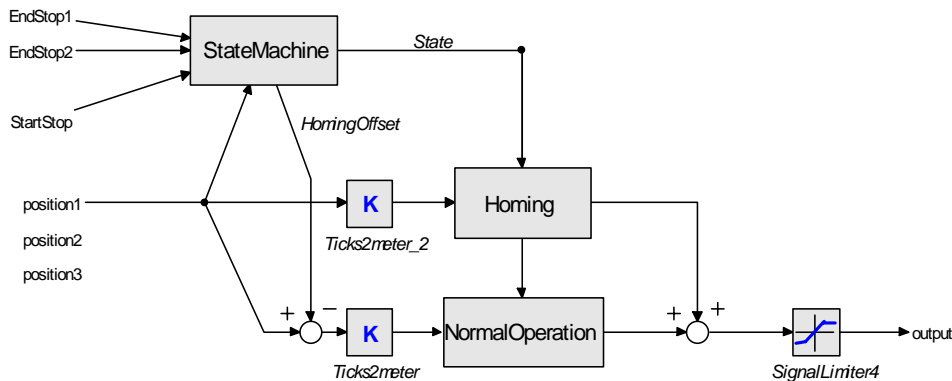


Figure 19 – Advanced Controller sub model

The advanced controller exists of a normal operation controller and a homing controller. The state machine has five different states:

State 0: The initial state waits until the start button is pressed while the emergency button is not pressed. Then go to state 1.

State 1: The homing operation is started and the slider moves to left until the left end stop is activated. This slider position is saved and then go to state 2.

State 2: The slider moves right until the right end stop is activated. This slider position is also saved. The next state is state 3.

State 3: The slider moves to home: The slider calculates the center with the left and right position values and the slider moves to this position.

State 4: The slider starts the normal operation.

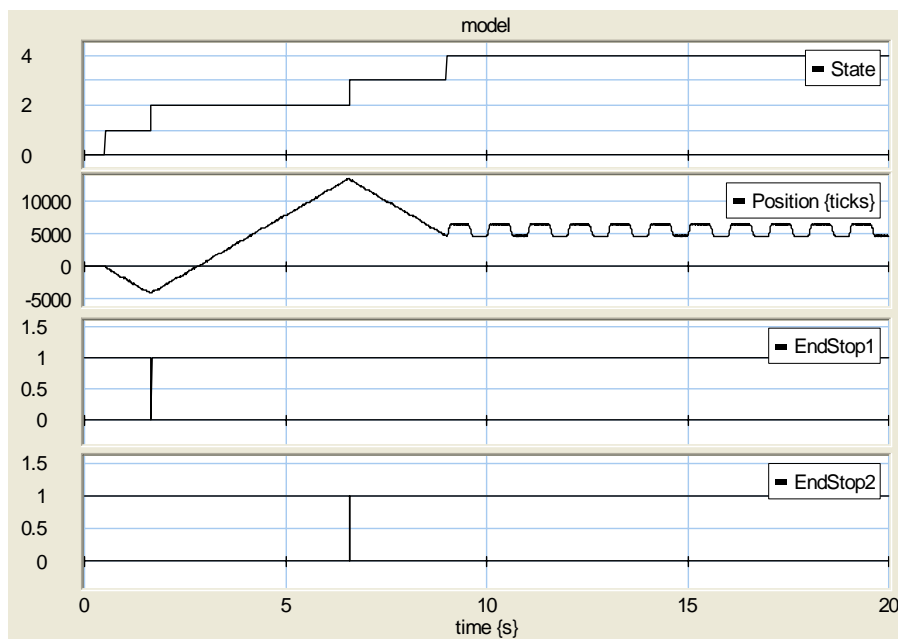


Figure 20 – Measurement results of the 20SIM model with homing functionality

Figure 20 shows some measurement values. The slider moves and activates the end stops. The end stops change the active state of the state machine. After the homing operation, the slider moves according to a block wave pattern which is controlled by the normal operation controller. In this simulation the slider does not start in the middle of the rail, so the homing operation creates an offset value. In Figure 19 the offset signal is subtracted of the slider position, so the controller moves the slider with a block pattern round the middle.

4.5 Conclusion

This section evaluates the improved functionality and if the problems are been solved sufficiently and if there are still possible restrictions. In section 1.2 the three imperfections of the end stops are discussed.

4.5.1 Motor brake functionality

The first problem is that the slider does not brake when an end stop is pushed. Because of this, damage can occur. The old electric circuit with the end stops does not brake the motor active. The solution is a new electric circuit that brakes the motor actively. This is realised with a TRIAC which is short circuited the motor.

The deceleration of the slider is increased from 4 m/s^2 to 40 m/s^2 . Because of this increased deceleration, the stop distance gets shorter, but the real stop distance is determined by the velocity of the slider. When the slider velocity is below 1.5 m/s , the stop distance should be acceptable (approximately 3cm). So a slider velocity limiter is recommended.

Further, it is recommend to replace the timing belt for a stronger one, because this one has reached the boundaries of its specification when the motor brakes with maximum power.

4.5.2 Direction dependency functionality

The second problem is the direction dependency of the end stops. This function is not implemented in the old end stop realization. In the old situation the power amplifier is disabled independently to the slider direction. When an end stop is activated the power amplifier is always disabled. The controller cannot enable the amplifier and also it cannot be enabled with a slider direction change.

To solve this problem a slider direction dependency motor brake is implemented. The electrical circuit contains logic to enable the motor amplifier when the set point is changed. This implementation is discussed in the previous chapter. With this implementation the problem is solved.

4.5.3 Homing functionality

The homing functionality of slider is the last problem. The start position of the slider was not defined. The position sensors of the slider detect only the relative position.

This problem is solved by a homing operation on start up of the controller. The end stops are connected to the controller. The controller uses the end stop status to do the homing operation. With this solution the last problem is solved.

5 Conclusions and Recommendations

5.1 Conclusions

This individual design assignment has resulted in an improved hardware safety layer. The end stops have more functionality and improve the safety of the Mechatronic Demonstrator.

- The motor brake is improved with a TRIAC. The TRIAC short circuits the motor to decelerate faster instead of the previous disabling of the motor amplifier. Thus, the motor stops faster. The deceleration of the slider is now maximal 40 m/s^2 instead of 4 m/s^2 .
- The end switches are now direction dependent, allowing the slider always to move away from the end switch.
- The end stops are connected to the computer (PC/104). With this end stop information a homing operation is added.

These new functionality is implemented on a printed circuit board. This bachelor assignment has resulted in an increased end stop functionality of the mechatronic demonstrator.

5.2 Recommendation

This section discusses some recommendations for further research.

- A software safety layer is recommended. This software prevents that the slider does not touch the end stops and so, it improves the solutions of the problems 1 and 2 of session 1.2.
- Implement a slider velocity limiter in software. The slider velocity has to limit to approximately 1.5 m/s .
- Implement the detection of the marker in the homing operation, because this detection is currently not implemented in the homing operation. Furthermore, examine the efficiency of the homing speed.
- Change the current timing belt for a stronger one, and replace the pulleys for bearing pulleys to pre-tension the belt.

Appendix A – Limiting motor velocity

In the safety layer for the demonstrator the motor velocity has to be limited. The velocity of the slider has to be limited to a maximum because the deceleration and the stop distance are not infinity. The velocity of the slider has to be limited to approximately 1 m/s. This limiting process can be done in hardware and software. This appendix discusses some hardware trials. The software solutions shall not be discussed in this report.

Four hardware solutions shall be explained:

1. A different power supply for the motor amplifier;
2. Voltage reduction of the motor;
3. Feedback of the (differentiated) motor position sensor to the motor brake;
4. Feedback of a motor voltage to the motor brake.

First, the effects of the voltage decreasing of the motor have to be discussed. The motor velocity is dependent of the motor voltage in accordance with formula:

$$u = K \Phi \omega$$

Further, the motor amplifier is used as current source, so the Torque is controlled.

$$T = K \Phi i$$

Also the acceleration α is controlled because:

$$T = I \alpha \text{ (Torque and acceleration are proportional, with constant inertia)}$$

So the motor torque and acceleration can be controlled by the current. But the maximum velocity is depended of the motor voltage.

A.1. Different power supply

Different power supplies can be used for the motor amplifier. The Maxon motor amplifier has a width input power supply range of 12 – 50 VDC. The voltage of the current power supply is 21.5 V and the maximum velocity of the motor is 88rev/s. But if the minimum voltage is used, then the motor velocity is 47rev/s by 12V. But the slider is still moving to hard.

A.2. Voltage reduction

In this experiment the voltage over the motor is reduced. The voltage must be reduced by a component that only reduced the voltage and not the current, so the torque and acceleration are not changed.

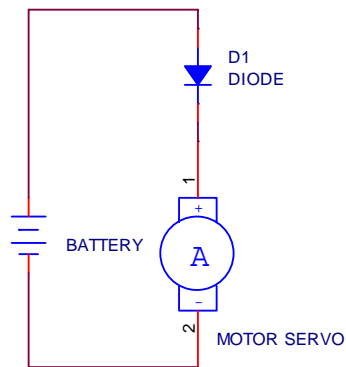


Figure 21 – Voltage of the motor is simply reduced by a diode

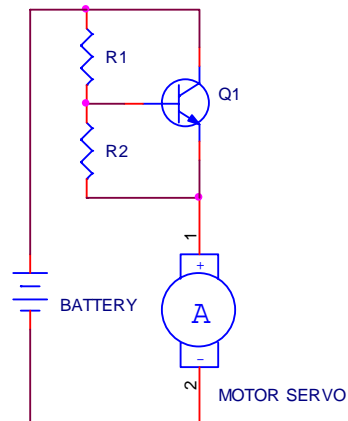


Figure 22 – Voltage of the motor is reduced by a power transistor which is simply configured by the resistors

The simplest method is to add a diode to the circuit. In Figure 21 the voltage of the motor is 0.6V lower than the battery. And in Figure 22 the voltage of the motor is reduced by:

$$v_0 = \frac{0.6V}{R_2} \cdot (R_1 + R_2)$$

$$V_{\text{motor}} = V_{\text{battery}} - V_0$$

The circuit of Figure 22 is tested in practice. The voltage of the PWM is reduced to 6.5V instead of 21.5V. Some results are shown in Figure 23.

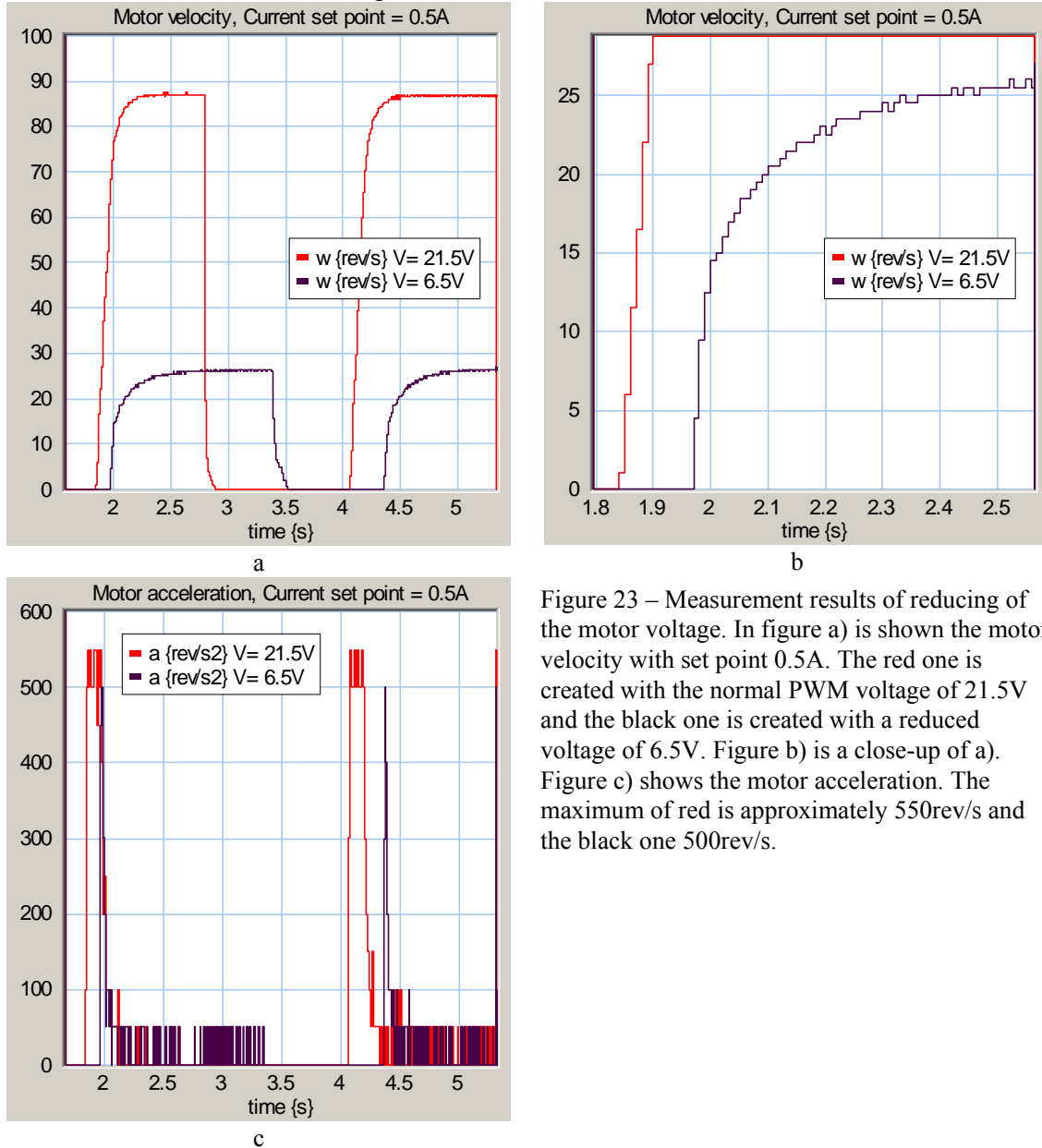


Figure 23 – Measurement results of reducing of the motor voltage. In figure a) is shown the motor velocity with set point 0.5A. The red one is created with the normal PWM voltage of 21.5V and the black one is created with a reduced voltage of 6.5V. Figure b) is a close-up of a). Figure c) shows the motor acceleration. The maximum of red is approximately 550rev/s and the black one 500rev/s.

The conclusion of this test is that it is possible to decrease the maximum motor velocity when the voltage is decreased. But the acceleration is not constant between 0 – 25rev/s. The acceleration decreases dependently of the motor voltage and this is not desirable. In general the motor acceleration is not constant in the last 20rev/s so the last increase of 5V can not be used.

This method is not desirable to limit the velocity of the slider, because the acceleration is not constant in the used range, so the limiter does not work adequate.

A.3. Feedback of the motor velocity

Solution 3 contains a feedback of the motor velocity to the motor brake. This is not easy to implement in hardware because the motor position sensor has to be differentiated, because the velocity is not measured. It is easier to implement this feedback in software.

A.4. Feedback of the motor voltage

Solution 4 contains a feedback of the motor voltage to the motor brake, because the motor voltage is proportional to the motor velocity. The PWM voltage of the motor has to be transformed to an effective voltage. Another method is to use the “monitor n”-output of the Maxon amplifier, but the amplifier is configured as current control. It is not so simple to implement a voltage feedback. This report shall not discuss this development or implementation.

Appendix B – Hardware connector configuration

This appendix contains the configuration of the hardware connector for the mechatronic demonstrator.

B.1. Input

Device 0: Sensoray 526

Type: Encoder

Channel 0: Motor angle {2000 ticks/revolution}

Channel 1: Slider position 1 (World) {40,000 ticks/m}

Channel 2: Slider position 2 (Top) {40,000 ticks/m}

Channel 3: Slider position 3 (Bottom) {40,000 ticks/m}

Type: Digital In

Channel 0: End stop 1

Channel 1: End stop 2

Channel 2: Status of Start/Emergency stop

Channel 3: NC

B.2. Output

Device 0: Sensoray 526

Type: DAC (digital analog converter)

Channel 0: Set point motor

Channel 1: NC

Channel 2: NC

Channel 3: NC

Type: Digital Out

Channel 0: LED Server Online

Channel 1: LED Model Started

Channel 2: NC

Channel 3: NC

Appendix C – Printed circuit board schematics

C.1. Main schematic

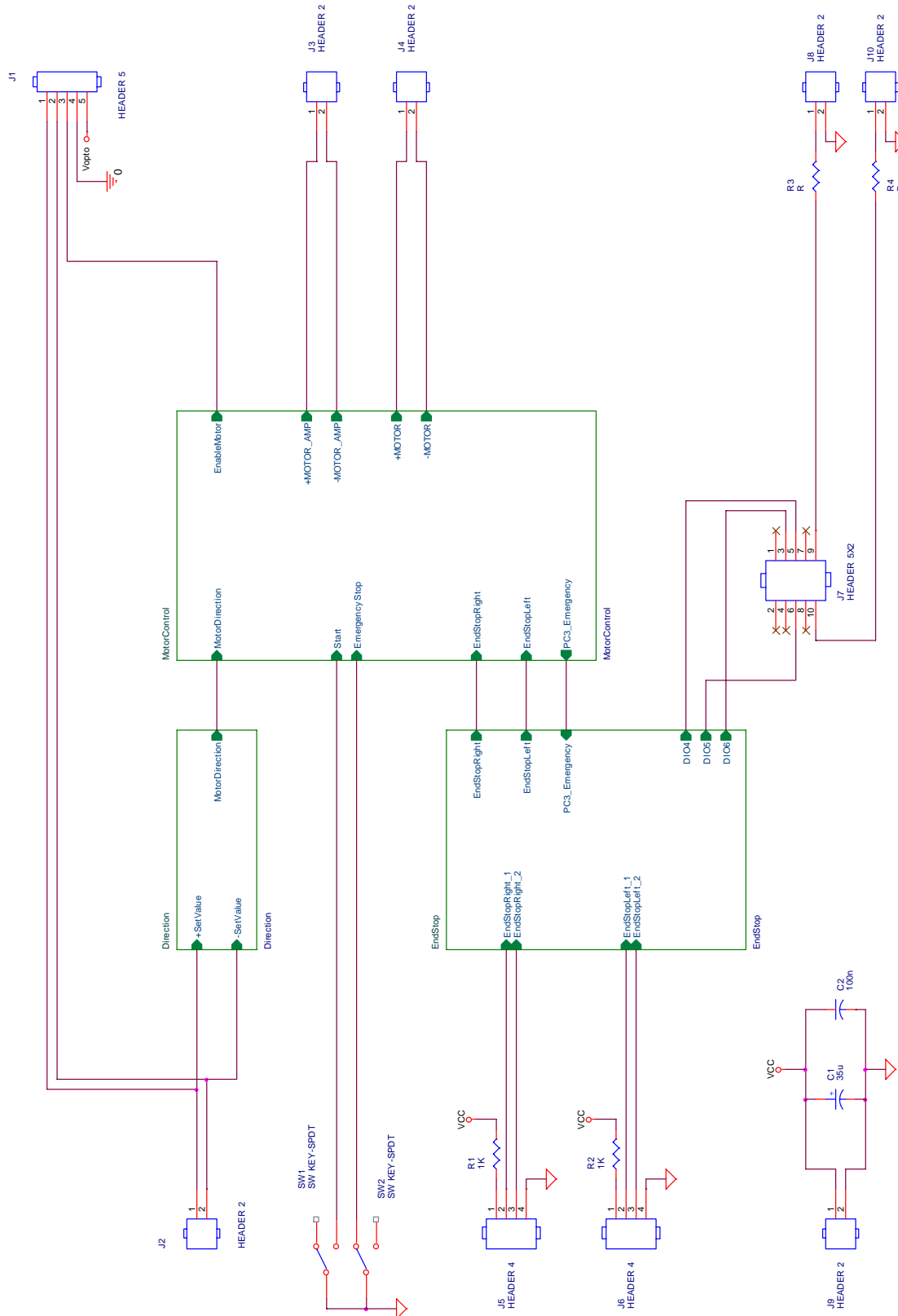


Figure 24 – Main schematic

C.2. Motor control schematic

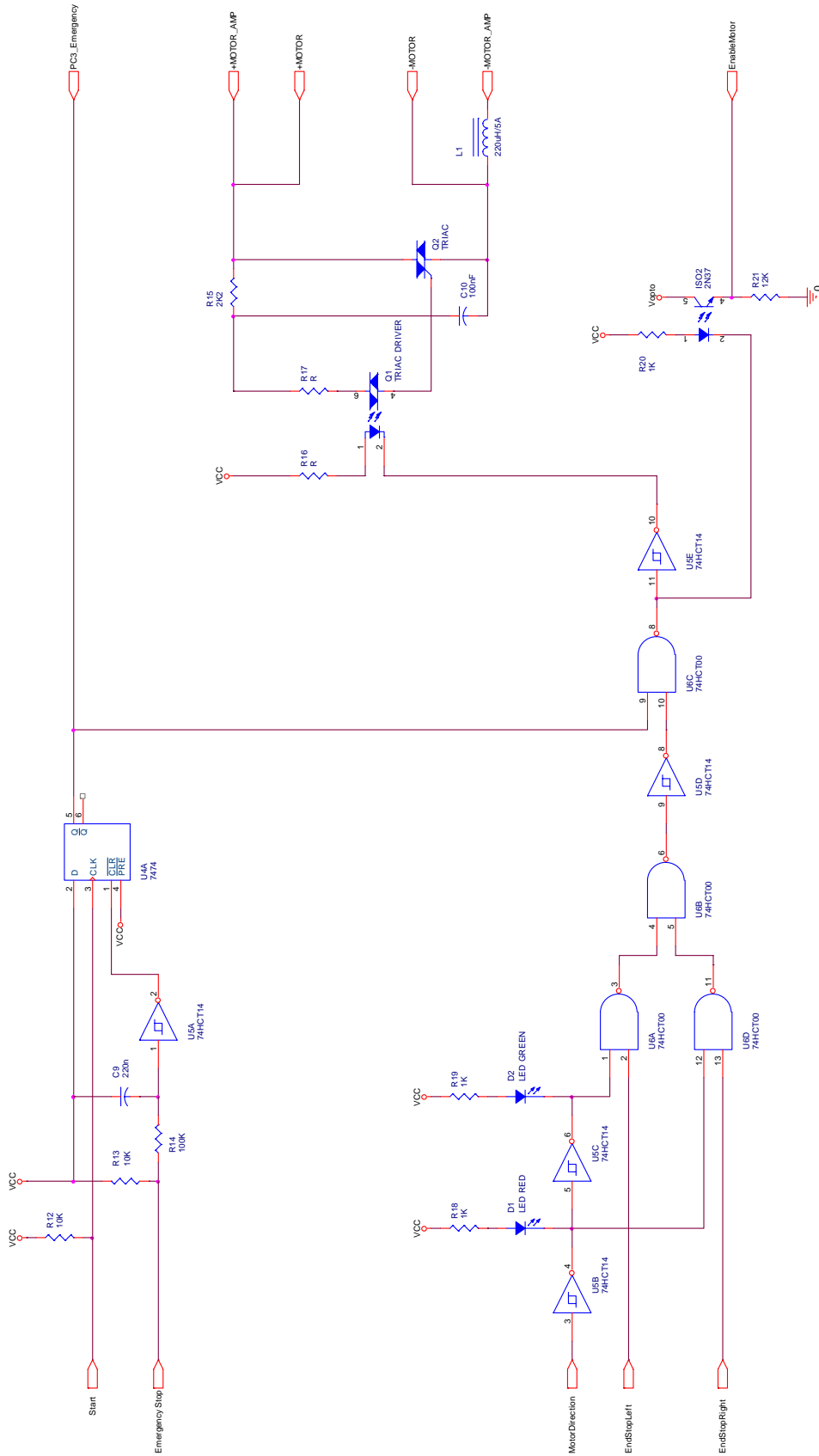


Figure 25 – Schematic of the logic and the short circuit of the motor

C.3. Direction schematic

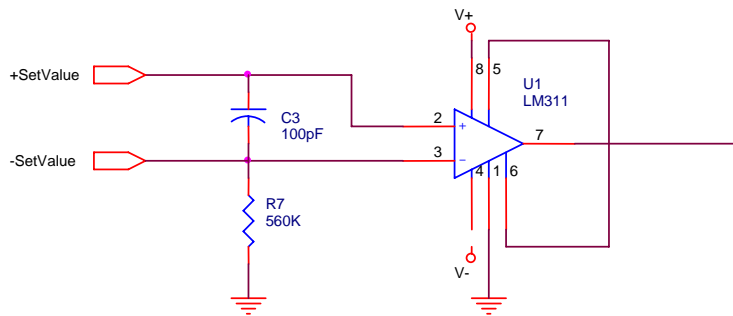


Figure 26 – Motor direction detector. The voltage comparator converts the analog voltage to a digital voltage.

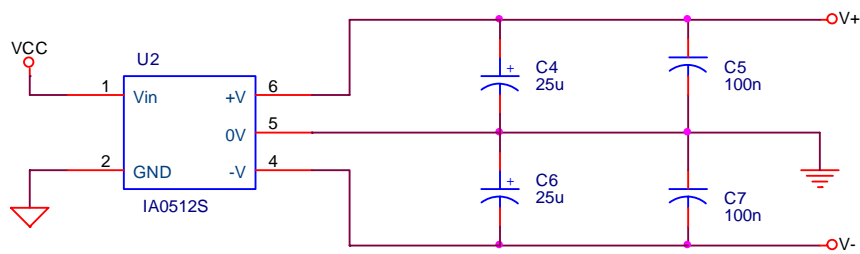


Figure 27 – DCDC-converter. It creates a +12V and -12V for the voltage comparator.

C.4. End stop schematic

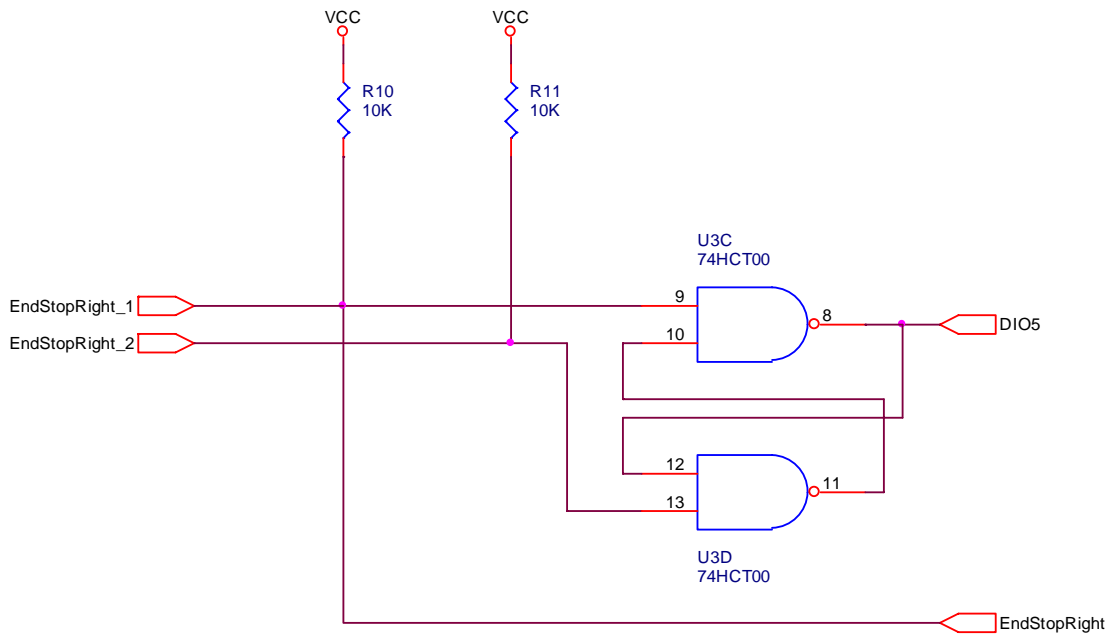
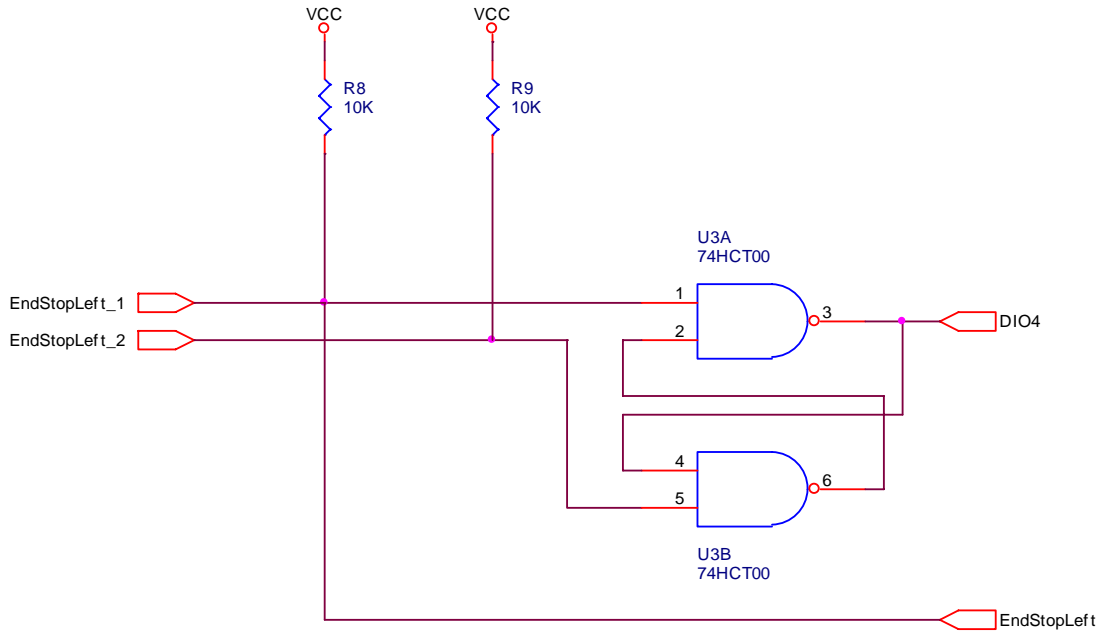


Figure 28 – Debounce circuits for the end stops

C.5. Remaining circuits

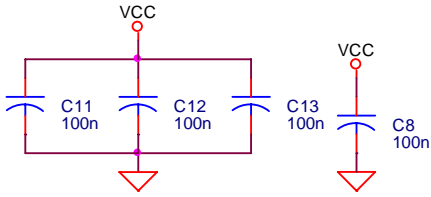


Figure 29 – Uncoupled capacitors

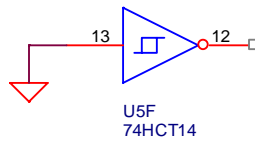


Figure 30 – The input of the not used inverter is grounded

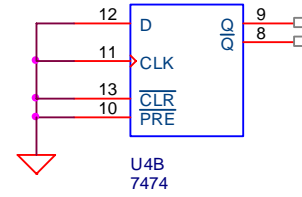


Figure 31 – The inputs of the not used D-flipflop are grounded

Appendix D – Printed Circuit Board Configuration

D.1. Connections overview

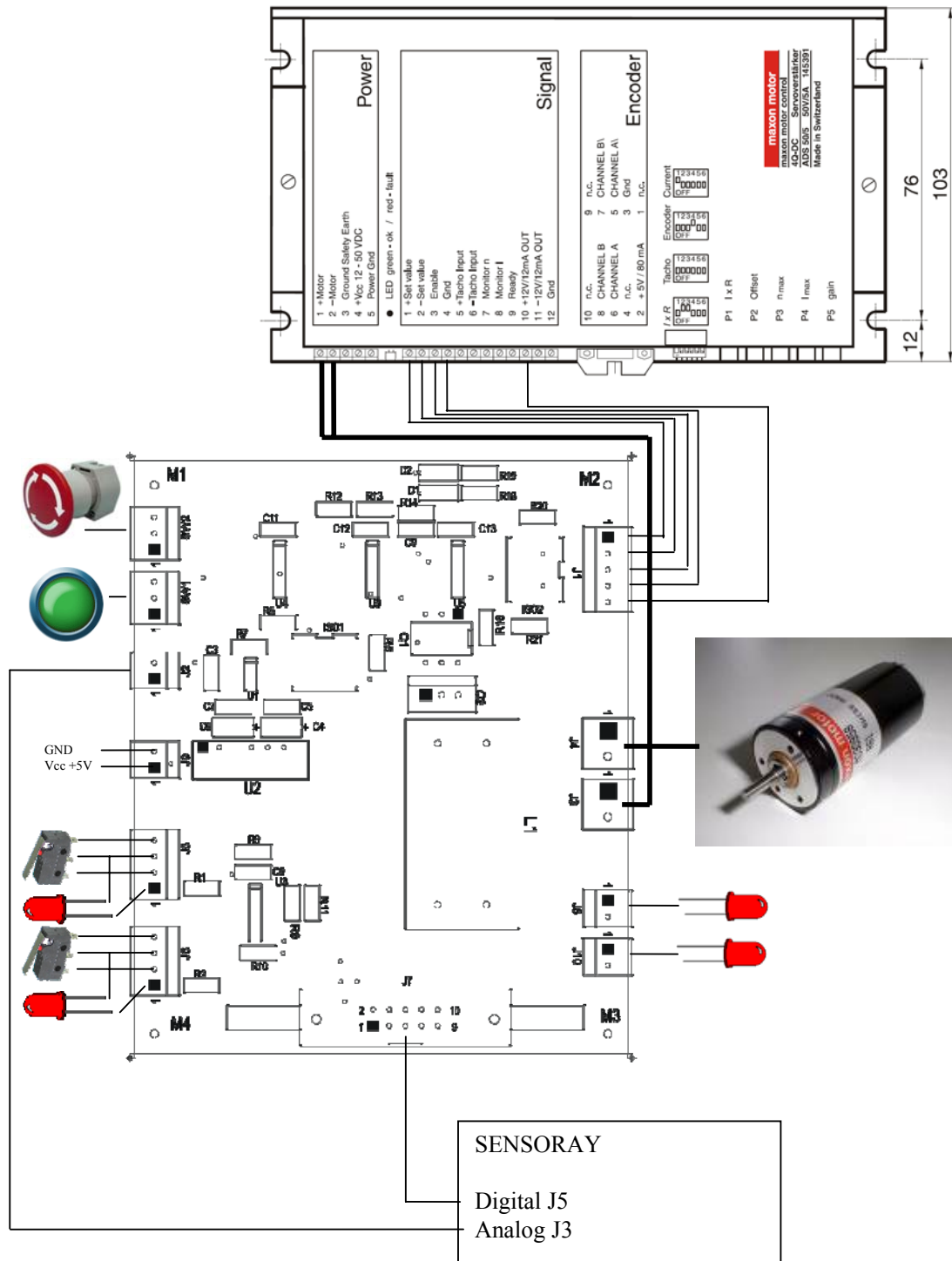


Figure 32 – Connections overview of the PCB

Appendix E – Part list printed circuit board

This appendix contains tables with components which are used on the PCB.

E.1. Resistors

Resistor	Value	Description
R1	50	Resistor for LED by end stop 1
R2	50	Resistor for LED by end stop 2
R3	550	Resistor for LED Server Online
R4	550	Resistor for LED Model Started
R5	2k2	LED of optocoupler
R6	5k	Transistor of Optocoupler
R7	560k	Input voltage comparator
R8	10k	Pull up resistor end stop 1
R9	10k	Pull up resistor end stop 1
R10	10k	Pull up resistor end stop 2
R11	10k	Pull up resistor end stop 2
R12	10k	Pull up resistor start button
R13	10k	Pull up resistor emergency button
R14	1k	RC-Delay for reset by start up
R15	10	Snubber network
R16	270	LED of TRIAC driver
R17	10	Triac driver
R18	200	LED red motor direction
R19	200	LED green motor direction
R20	1k	LED Optocoupler Enabling amp.
R21	12k	Transistor Optocoupler Enabling amp.

Table 4 – Resistor overview of the PCB

E.2. Capacitors

Capacitor	Value(F)	Description
C1	35 μ	Vcc 5V
C2	100n	
C3	100p	Input voltage comparator
C4	25 μ	Supply +12V
C5	100n	
C6	25 μ	Supply -12V
C7	100n	
C8	100n	

C9	220n	RC-delay for reset by start up
C10	100n	Snubber network
C11	100n	
C12	100n	
C13	100n	

Table 5 - Capacitors overview of the PCB

E.3. Remaining components

Component	Description	Farnell part number	Price (euro)
D1	SMD LED red	1142617	0.32
D2	SMD LED green	1142615	0.24
ISO1	Opto isolator	1021184	0.33
ISO2	Opto isolator	1021184	0.33
L1	Inductor – Choke 120 μ H 6A	1187672	4.08
Q1	K3010P – Triac driver	4402900	0.52
Q2	Triac – BTA08-600BRG, 8A 600V	1057269	0.63
U1	LM311 – Voltage comparator	2293183	0.189
U2	IA0512S – DCDC converter 5V to +/-12V	8727503	5.81
U3	74HCT00 – Quad NAND-gate	1236257	0.196
U4	7474 – D-Type Flip-flop	1013996	0.27
U5	74HCT14 – Inverter-Gate	1236216	0.23
U6	74HCT00 – Quad NAND-gate	1236257	0.196

Table 6 – Part list of used components for the PCB.

The sum price of the components is € 13.34 exclusive the resistors, capacitors and the connectors.

Appendix F – Connectors user manual

In this appendix the connectors of the PCB will be explained, for each connector the pin layout is given.

F.1. Connector J1 – Control signals to the motor amplifier

The PCB is connected to the motor amplifier. The set point and the enable signal were connected to the amplifier. A separated ground is used with pin 2. The enable signal is separated optical with an optocoupler. This optocoupler has a transistor outputs witch are connected to pin 3, 4, 5.

Connector pin#	Function	MAXON Motor amplifier
1	+Set point, analog -10...10V	Signal pin 1
2	-Set point, analog ground	Signal pin 2
3	Enable of the amplifier	Signal pin 3
4	Ground of the amplifier	Signal pin 4
5	+12V of the amplifier	Signal pin 10

F.2. Connector J2 – Set point of the Controller

The PCB gets the Set point with this connector from the ADC (Sensoray). The set point is an analog value between -10 and 10V.

Connector pin#	Function	SENSORAY - J3 (Analog)
1	+Set point, analog -10...10V	Pin 23
2	-Set point, analog ground	Pin 25

F.3. Connector J3 – Motor power of the amplifier

The output power of the amplifier is connected to the PCB with connector J3.

Connector pin#	Function	MAXON Motor amplifier
1	+Motor	Power pin 1
2	-Motor	Power pin 2

F.4. Connector J4 – Motor power to the motor

The motor is connected to J4.

Connector pin#	Function
1	+Motor
2	-Motor

F.5. Connector J5 and J6 – End stops with LED

The pin configurations of both end stop connectors are the same. The status LED is directly mounted on the switch. The LED is on when the switch is pushed.

Connector pin#	Function
1	LED anode
2	Switch, Normally Closed
3	Switch, Normally Open + LED cathode
4	Switch, Common (Ground)

F.6. Connector J7 – Digital Input Output

With this connector the digital IO with the controller is realized. The connector has status information about the end switches and the status of the start/emergency switch. The outputs have information about the status LEDs of the front panel of the Mechatronic Demonstrator (Connectors J8 and J10).

Connector pin#	Function	SENSORAY - J5 (Digital) pin#
----------------	----------	------------------------------

1	Not Connected	49
2	Not Connected	50
3	DIO6 Input – Status of Start/Emergency stop	47
4	DIO7 Not Connected	48
5	DIO4 Input – End Stop 1	45
6	DIO5 Input – End Stop 2	46
7	DIO2 Not Connected	43
8	DIO3 Not Connected	44
9	DIO0 Output – LED Server Online	41
10	DIO1 Output – LED Model Started	42

This connector is connected to the Sensoray board. This Sensoray connector has to configure right in hardware and software. The DIO has been manually configured as inputs respectively outputs in groups of 4 bits. The DIO 0-3 are outputs and DIO 4-7 are inputs. The outputs have an output current of 25mA drive/sink. The input pull-up resistor is 10kOhm.

F.7. Connector J8 and J10 – Status LEDs

The two LEDs are red status LEDs. The “Server Online”-LED is connected with connector J8 and the “Model started”-LED is connected with connector J10. Both LEDs are mounted on the front panel of the Mechatronic Demonstrator.

Connector pin#	Function
1	Anode
2	Cathode (Ground)

F.8. Connector J9 – Power supply

This is the power connector of the print. The power is obtained of the 5V computer power supply.

Connector pin#	Function
1	Vcc (+5V)
2	Ground

F.9. Connector SW1 – Start or Set switch

This connector connects the green start button to the PCB. The button enables the PCB after the emergency button is pushed and reset.

Connector pin#	Function
1	Switch, Common (Ground)
2	NC
3	Switch, Normally Open

F.10. Connector SW2 – Emergency switch

This connector connects the red emergency button to the PCB.

Connector pin#	Function
1	Switch, Common (Ground)
2	Switch, Normally Closed
3	NC

Appendix G 20SIM sub models

```

parameters
    integer initial_logic_state = 0;
    // 0 is initial state
    // 1 is going left
    // 2 is going right
    // 3 is going home
    // 4 is at home

variables
    integer logic_state, new_logic_state;
    real position_left, position_right;
    real new_position;

initialequations
    new_logic_state = 0;
    position_left = 0;
    position_right = 0;
    HomingOffset = 0;
    State = 0;

code
    // definition of logic state itself
    logic_state = previous (new_logic_state, initial_logic_state);

    // logic state transitions (switch-case)
    switch logic_state
        case 0 do // stop
            if (StartStop == 1) then
                new_logic_state = 1;
            end;
        case 1 do // go left
            if (EndStop1 == 0) then
                position_left = Position;
                new_logic_state = 2;
            end;
        case 2 do // go right
            if (EndStop2 == 0) then
                position_right = Position;
                new_logic_state = 3;
            end;
        case 3 do // go home
            if (new_position < 0) then
                new_logic_state = 4;
            end;
        case 4 do // @home
            if (StartStop == 0) then
                new_logic_state = 0;
            end;
        default do
            new_logic_state = 0;
    end;

equations
    State = logic_state;
    HomingOffset = (position_right - position_left)/2 + position_left;
    new_position = Position - HomingOffset;

```

Figure 33 – 20SIM code of the State Machine sub model

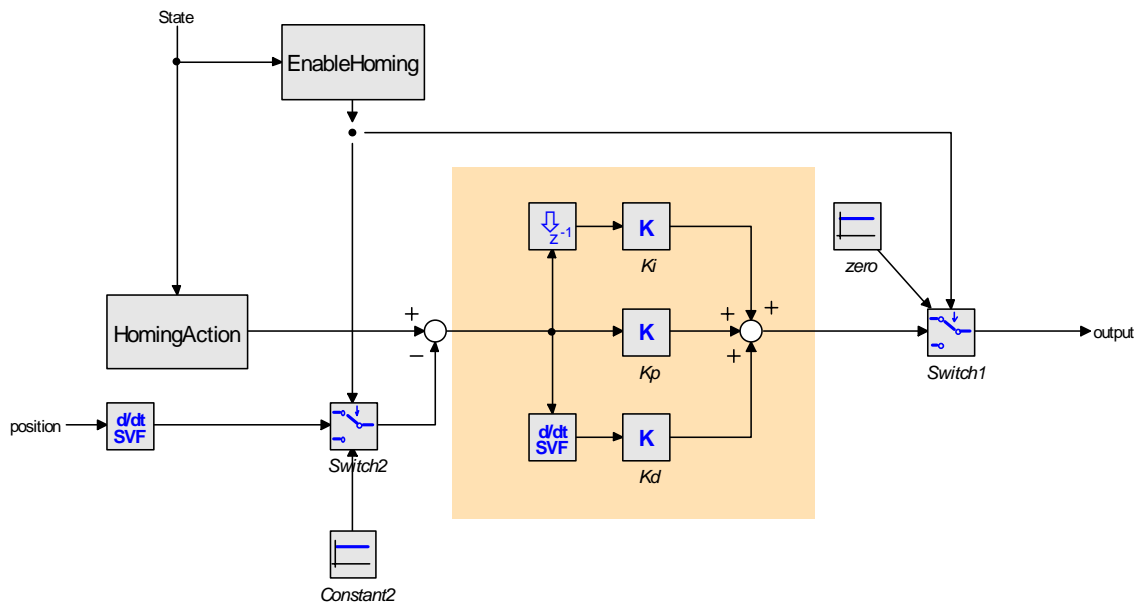


Figure 34 – 20SIM sub model: Homing

```

parameters
    real homingVelocity = 0.1 {m/s}; // 2 cm/seconds homing velocity
    // 0 is not active
    // 1 is going left
    // 2 is going right
    // 3 is going home
    // 4 is at home
initialequations
    output = 0;
code
    // logic state equations (switch-case)
    switch State
        case 0 do
            output = 0; // stop
        case 1 do
            output = -homingVelocity; // go left
        case 2 do
            output = homingVelocity; // go right
        case 3 do
            output = -homingVelocity; // go home
        case 4 do
            output = 0; // @home
        default do
            output = 0;
    end;
    
```

Figure 35 – 20SIM code of the sub model: HomingOperation

```

parameters
    real side = 0.435 {m};
initialequations
    EndStop1 = 1;
    EndStop2 = 1;
equations
    EndStop1 = if ( Position < 0 ) then 0 else 1 end;
    EndStop2 = if ( Position > side ) then 0 else 1 end;
    
```

Figure 36 – 20SIM code of the EndStopSimulator sub model

Appendix H Characterization of the demonstrator

In this appendix some calculations have been done to stipulate the theoretical value of the follow parameters:

- maximal acceleration
- maximum torque;
- maximum current;
- maximum velocity;
- maximum stop distance.

<p>Belt</p> <p>The belt that is used for the demonstrator has the following specifications (datasheet of the belt):</p> <p>Width: 3 mm and a pitch: 2.032 mm;</p> <p>Maximum Operating Tension: 7 N;</p> <p>Maximum Speed up to 20,000 rpm.</p>
<p>Pulley</p> <p>Type: TP7A6MW2-24</p> <p>Number of teeth: 24</p> <p>Diameter: 15.52 mm</p>
<p>Rail and slider</p> <p>Under normal operation conditions the permissible speed is 3 m/s and the accelerations up to 80 m/s² (datasheet of the rail).</p> <p>Slider mass: 0.119 kg (Kleijn, 2003).</p>
<p>Motor</p> <p>Type: RE 35 Ø35 mm, Graphite Brushes, 90 Watt DC-motor (Datasheet of the motor)</p> <p>Torque constant: 38.9 mN.m/A</p>
<p>Motor supply</p> <p>Type: Maxon motor control 4-Quadrant-DC ADS 50/5 (Datasheet of the amplifier)</p>

Table 7 – Some characteristics of the demonstrator

H.1. Required Force for maximal acceleration

The maximum, allowed acceleration of the rail and slider is published by the supplier in the datasheet. The maximum acceleration is 80 m/s². The slider has a mass of 0.119 kg. The calculated force is $F = 0.119 \cdot 80 = 9.52 \text{ N}$. But the maximum force of the belt is only 7 Newton in the datasheet.

H.2. Maximum Torque

The maximum torque can be calculated by: $\text{Torque} = F \cdot r_{\text{pulley}}$. The used force in this calculation is the lowest force of the belt: 7 Newton. The pulley has a radius of 7.76mm. So the maximum torque is:
 $\text{Torque} = F \cdot r_{\text{pulley}} = 7\text{N} \cdot 0.00776\text{m} = 0.05432 \text{ N.m}$.

H.3. Maximum current

The maximum current to deliver this torque can be calculated to divide by the motor constant. The motor has a torque constant of 38.9mN.m/A. So the maximum current is $0.05432/0.0389 = 1.4 \text{ A}$.

The current limiter is configured with a maximum current of 1A. When the set point of the controller is at maximum (=1.0) then the supplied current is 1A. So the maximum delivered force is lower than the maximum force of the rail and belt. And the motor is unable to damage the slider.

H.4. Maximum velocity

The maximum velocity has to calculate. The maximum torque by 1A is current times torque constant $1\text{A} \cdot 38.9\text{mN.m/A} = 38.9\text{mN.m}$. The Force can be calculated by $T = F \cdot r$,

$$F = \frac{T}{r} = \frac{0.0389}{0.00776} = 5.0\text{Newton}$$

The maximum acceleration is

$$a = \frac{F}{m} = \frac{5\text{N}}{0.119\text{kg}} = 42.0\text{m/s}^2$$

When friction is neglected the maximum acceleration is 42.0m/s^2 and in 20cm the maximum velocity can be calculated:

$$v = a \cdot t$$

$$x = \frac{1}{2} \cdot a \cdot t^2$$

$$t = \sqrt{\frac{2 \cdot 0.2\text{m}}{42.0\text{m/s}^2}} = 0.098\text{s} \text{ (The required time to move 20cm at maximum acceleration.)}$$

$$v = a \cdot t = 42 \cdot 0.098 = 4.1\text{m/s} \text{ (Theoretical and neglected friction)}$$

The theoretical maximum velocity of the slider is 4.1m/s.

In the next graph (Figure 37) the real velocity is measured. The slider moves approximately 20 cm over the rail.

H.5. Measured velocity

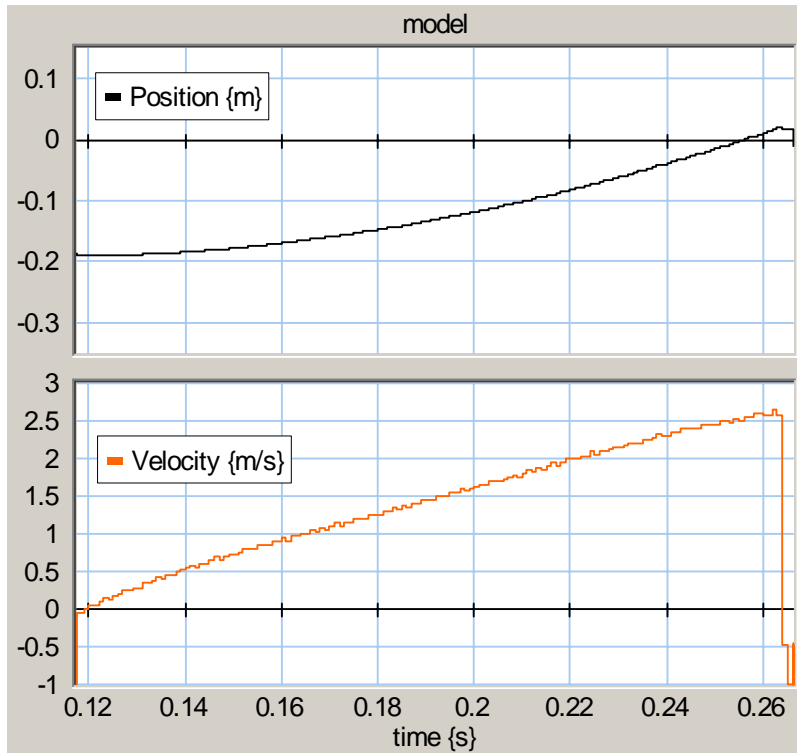


Figure 37 - Measurement results: position and velocity of the slider

The velocity of the slider is dependent on the friction of the rail and the tension of the belt and the current of the motor. The maximum measured velocity is 2.6 m/s. The difference between the measured and the theoretical values can be explained, because in the theoretical calculation some imperfection of the slider friction is neglected.

H.6. Required stop distance

The stop distance of the slider is dependent to the velocity and the deceleration or the force. The maximum velocity of the slider is 2.6m/s and the maximum force is 7N.

$$\text{The deceleration is } a = \frac{F}{m} = \frac{7N}{0.119kg} = 58.8m/s^2.$$

$$\text{The stop time is } t = \frac{v}{a} = \frac{2.6m/s}{58.8m/s^2} = 0.044s$$

and the stop distance is $s = v \cdot t = 1.3m/s \cdot 0.044s = 5.7cm$.

The maximum available stop distance is 3cm, because first, the free space of the slider is too restricted to a longer stop distance. Further, with the current end stops the slider can pass the switch when the stop distance is too long. So the end stop is switched on and off when the slider is passed.

The preferred stop distance is 3 cm or shorter. Because:

- With a longer stop distance on both sides, the free space of the slider is too restricted.
- With a longer stop distance, the slider can pass the current used switch, because the length of the slider is 3 cm too.
- With a shorter stop distance the velocity of the slider has to decrease or the braking force has to increase. The maximal allowed force of the belt is 7 Newton.

Literature

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