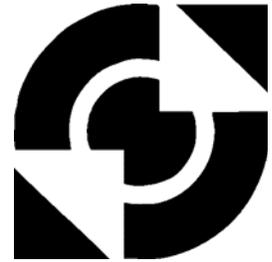


# University of Twente

EEMCS / Electrical Engineering  
*Control Engineering*



## **Mechatronic setup for Boderc project**

---

**M. Otto**

**M.Sc. Thesis**

---

### **Supervisors**

prof.dr.ir. J. van Amerongen  
dr.ir. J.F. Broenink  
dr.ir. G.J.M. Smit  
ir. E. Molenkamp  
ir. P.M. Visser

October 2005

Report nr. 038CE2005  
Control Engineering  
EE-Math-CS  
University of Twente  
P.O. Box 217  
7500 AE Enschede  
The Netherlands

---



---

## Summary

Modern large scale projects, such as the development of high velocity printers, rely on knowledge from several different disciplines. Traditionally every discipline has its own design methods and development techniques. In the Boderc project several companies and universities work together to find a good systematic approach for the development of distributed embedded real-time controllers for complex systems. The focus of the University of Twente in this project is distributed control. One of the goals is to use an experimental setup which will be used as a proof of concept of hardware in the loop simulation.

This thesis describes the experimental setup that is created and integrated with an earlier developed embedded architecture. The result is a mechatronic setup that represents a part of the paperpath of a high velocity printer.

The complete mechatronic setup, which includes the controller and the mechanical setup, is called Mechatronic Simulation Setup or MESS. The mechanical and interfacing part of the setup is called Paperpath Simulation Setup or PASS. The requirements are based on application experiments of the Boderc project, which define the global architecture of the PASS. The PASS consists of a paper input module, four pinches and an output tray. The paper input module feeds paper sheets to the paperpath. Pinches transport the paper sheets through the paperpath and the output tray collects the paper sheets. Sheet detectors are used to detect paper sheets at fixed positions and the rotation of the motors of the paper input module and pinches are measured by quadrature encoders. All the sensors and actuators are connected to the embedded controller by an interface. The embedded controller consists of four embedded stacks (computing nodes).

Scenarios are used to describe the connections between the PASS and the embedded stacks. The developed interface consists of five small interface prints which each support for 3 motors, 3 quadrature encoders, 8 sheet detectors and an array sensor. These interface prints are connected to the embedded stacks with a flat cable. Normally each pinch and the paper input module has their own interface print. This way it is easy to connect a pinch to another embedded stack to test different control architectures.

The embedded stacks are adapted to provide a connection to the interface prints. Each embedded stack has an FPGA interface card which provides the necessary input and output. An FPGA architecture is developed for the interface card. This architecture consists of a Bridge Interface Module for the communication with the controller and several modules which provide the resources for the actuators and sensors.

Experiments were performed to validate the performance and accuracy of the MESS. The results of the experiments show that most requirements are met. A calibration method is described to determine the position and accuracy of the sensors and actuators.

The MESS is working and the crucial parts are finished. Together with a model of the PASS it provides a good simulation platform which can be used to verify hardware in the loop simulations. The interface prints provide flexible connections to the embedded controller. This makes it easy to test different control architectures, centralized as well as distributed. The MESS is capable to handle over one hundred pages per minute.

Experiments show that the paper input module sometimes inserts two paper sheets at the same instant. Solutions are suggested to prevent this. Furthermore, a control panel is a valuable extension to the MESS. The interface prints contain facilities for this purpose.

## Samenvatting

Moderne grootschalige projecten, zoals de ontwikkeling van hoge snelheids printers, gebruiken kennis uit verschillende disciplines. Traditioneel heeft elke discipline zijn eigen ontwerp en ontwikkel methodes. Verscheidene bedrijven en universiteiten werken in het Boderc project samen aan de ontwikkeling van een goede systematische benadering voor de ontwikkeling van gedistribueerde embedded real-time regelaars voor complexe systemen. In dit project ligt de aandacht van de Universiteit van Twente in gedistribueerde regelaars. Een van de doelen is de ontwikkeling van een experimentele opstelling die gebruikt kan worden om de conceptuele werking van hardware in de loop simulaties aan te tonen.

Dit rapport beschrijft de ontwikkelde experimentele opstelling en de integratie met een eerder ontwikkelde embedded architectuur. Het resultaat is een mechatronische opstelling die een deel van het papierpad van een hoge snelheids printer representeert.

De complete mechatronische opstelling, bestaande uit een regelaar en de mechanische opstelling, heeft de naam Mechatronic Simulation Setup, of afgekort MESS. Het mechanische deel en de interface hebben de naam Paperpath Simulation Setup, of afgekort PASS. De eisen zijn gebaseerd op applicatie experimenten van het Boderc project en definiëren de globale architectuur van de PASS. De PASS bevat een papier invoer module, vier knepen en een opvangbak. The papier invoer module voert papier in het papierpad. De knepen transporteren het papier door het papierpad naar de opvangbank waar het papier verzameld wordt. Papier detectoren worden gebruikt om het papier op vaste posities te detecteren. De rotatie van zowel de papier invoer module als de knepen wordt gemeten met behulp van kwadratuur encoders. Een interface print verbindt alle sensoren en actuatoren met de embedded regelaar. De embedded regelaar bestaat uit vier embedded stacks (computerende eenheden).

De verbindingen tussen de embedded stack en de PASS worden gedefinieerd door scenario's. De ontwikkelde interface bestaat uit vijf kleine interface prints die elke faciliteiten hebben voor 3 motoren, 3 kwadratuur encoders, 8 papier detectoren en een array sensor. De interface printen worden met behulp van een flat cable verbonden met de embedded stacks. Normaal heeft elke papier input module of kneep een eigen interface prints. Hierdoor is het gemakkelijk om een kneep aan een andere embedded stack te koppelen en zo een andere regel architectuur te testen.

De embedded stack is aangepast om de verbinding met de interface prints mogelijk te maken. Een FPGA interface kaart voorziet elke interface kaart van de benodigde input en output. Er is een FPGA architectuur ontwikkeld voor deze interface kaart. Deze module gebaseerde architectuur bevat een Bridge Interface Module om te communiceren met de regelaar en extra modules voor de ondersteuning van de actuatoren en sensoren.

Experimenten zijn uitgevoerd om de werking en de precisie van de MESS vast te stellen. De resultaten van de experimenten laten zien dat aan de meeste van de gestelde eisen wordt voldaan. Een kalibratie methode is beschreven om de positie en precisie van de actuatoren en sensoren vast te stellen.

De MESS werkt en de cruciale onderdelen zijn af. Samen met een model van de PASS biedt the MESS een goed platform voor het verifiëren van hardware in de loop simulaties. De interface printen bieden een flexibele verbinding met de embedded regelaar. Hierdoor is het eenvoudig om verschillende regel architecturen te testen, zowel gecentraliseerd als gedistribueerd. The MESS kan meer dan honderd pagina's per minuten doorvoeren.

Uit experimenten bleek dat de papier invoer module soms twee vellen papier tegelijk invoerde. Oplossing om dit te voorkomen zijn aangedragen. Een controle paneel zou een goede toevoeging zijn voor de MESS. De interface printen hebben hier faciliteiten voor.

## Contents

1	Introduction.....	1
1.1	Project background .....	1
1.2	Previous work .....	2
1.2.1	Distributed HIL simulation of Boderc.....	2
1.2.2	PC104 stack mechatronic control platform .....	4
1.3	Project description .....	4
1.4	Report outline .....	5
2	Global Architecture.....	7
2.1	Introduction to the MESS .....	7
2.1.1	Aspects of the PASS.....	7
2.1.2	Overview of MESS.....	8
2.2	Requirements .....	9
2.2.1	Application areas .....	9
2.2.2	Application experiments.....	9
2.2.3	Characteristics summary .....	10
2.3	Global design choices .....	10
2.4	Global architecture off the PASS.....	12
3	Mechanical and electrical design .....	15
3.1	Mechanical.....	15
3.1.1	Design choices.....	15
3.1.2	Detailed Design .....	18
3.1.3	Construction & Result .....	20
3.2	Electrical .....	21
3.2.1	Design choices.....	21
3.2.2	Detailed design.....	23
3.2.3	Implementation.....	24
3.3	Integrated PASS.....	25
4	MESS integration .....	27
4.1	Architecture .....	27
4.2	FPGA Design.....	27
4.2.1	Global design.....	28
4.2.2	Design details .....	29
4.2.3	Implementation.....	30
4.2.4	MSCT integration.....	30
4.2.5	Result.....	31
5	Experiments and results .....	33
5.1	Experiments environment .....	33
5.2	Unit experiments.....	33
5.2.1	Interfaces .....	33
5.2.2	Actuators and sensors .....	34
5.2.3	PIM.....	34
5.3	Integrated experiments.....	36
5.3.1	Controller design .....	36
5.3.2	Parameter calculations.....	37
5.3.3	Single controller .....	37
5.4	Calibration .....	38
5.4.1	Introduction .....	38
5.4.2	Measurement errors .....	39
5.4.3	Roller circumference .....	39
5.4.4	Calibration of the pinches.....	40
5.4.5	Calibration of the sheet detectors .....	41
5.5	Validation .....	42

6	Conclusions and Recommendations.....	43
6.1	Conclusions.....	43
6.2	Recommendations.....	44
Appendix I	Requirement analysis .....	47
Appendix II	Motor and gear selection .....	51
Appendix III	Construction document.....	56
Appendix IV	Scenarios .....	67
Appendix V	Electrical design .....	72
Appendix VI	FPGA Design .....	80
Appendix VII	Experiments.....	84

# 1 Introduction

Modern large scale projects, such as for instance the development of high velocity printers, production robots or space equipment, rely on knowledge from different disciplines. Traditionally every discipline has its own design methods and develops its own parts. This is often done without looking at the effects their decision have on the other disciplines. This could lead to problems during integration which can mean that certain requirements cannot be met, an increase of time and costs or redesigns. This is why in 2002 the Embedded System Institute started a research into multidisciplinary system design. In the project called Boderc several companies and universities work together to find a good systematic approach for the development of distributed embedded real-time controllers for complex systems. To test this approach a high speed Océ copier is used as a test case. A part of the group will use a demonstration setup to validate their approach and test control architectures. The development of this demonstration setup is the subject of this thesis.

## 1.1 Project background

Before explaining the scope of the project a little background is presented. In the background various terms and abbreviations are introduced which will be used throughout this thesis. The focus of this background will lie on aspect relevant to this project. The modeling language 20-Sim is introduced as well. 20-Sim and the mentioned features are used in this project.

### **Boderc**

Boderc stands for “Beyond the Ordinary: Design of Embedded Real-time Control” (Boderc, 2005). The Boderc project focuses on distributed embedded real-time controllers of complex systems. Often problems occur during the integration phase of such complex system. These problems lead to delayed time to market. The Boderc project is based on the hypothesis that the time to market can be reduced by using multi-disciplinary models during the early phases of the product development. The target is an integral approach for a systematic architectural design, modeling, analysis, and validation methodology of such heterogeneous systems. Examples of the areas where this method is expected to help are the prediction of system performance and communication between engineers from different disciplines. Océ is the carrying industrial partner of the project. A high velocity copier from Océ is used as a test case.

The project is divided in several groups which each tackle a part of the problem. The Control Engineering group (CE) of the University of Twente (UT) is part of the group which has as main focus distributed control. One of their goals is to create an experimental setup which can be used as a proof of concept of Hardware in the loop. During the experiments different types of control architecture will be tested.

### **Hardware in the loop**

Hardware in the loop (HIL) simulations is a type of real time simulation. More details on HIL simulation can be found in (Isermann *et al.*, 1998). Real time simulation is increasingly being used during the design, implementation and testing of control systems of mechatronic designs. Real time simulation means that the input and the output signals of the controller show the same time dependent behavior as the real dynamical system. There are several kinds of real time simulation methods which are shown in Figure 1

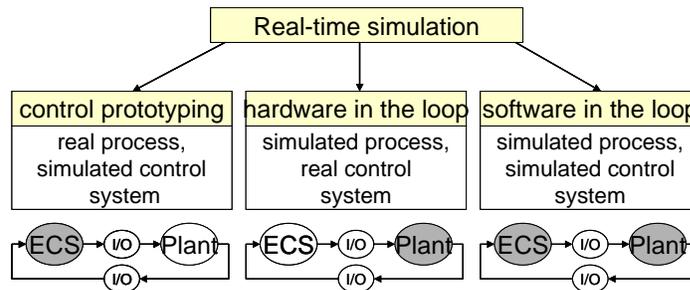


Figure 1 - Classification of real-time simulation (Isermann *et al.*, 1998)

In case of the HIL simulations the controller is the real system and the process is simulated. An important aspect in HIL simulation is the border between the physical process and the control system. A choice has to be made for the actuators and sensors of the physical process. They can be real, simulated or partially simulated.

Because the real process is not needed there are a number of advantages as a result of using HIL simulation. Among them are:

- Development and testing of the control system can be performed before the real system is developed
- Testing of extreme conditions can be performed without the change of damaging the real system.
- Test conditions can easily be reproduced.

## 20-Sim

20-Sim is a modeling and simulation program. 20-Sim can be used to create models of dynamic system and perform simulations with these models. The models are created in a graphical environment in which either IPM symbols or bond graphs can be used.

The Real Time Toolbox provides C-code generation tools. With the help of template these tools can be used to generate stand alone programs which can run on different targets.

The Mechatronics Toolbox assists in the development of mechatronic designs. The Mechatronics Toolbox contains a Servo Motor Editor which is developed in cooperation with motor manufacturers (e.g. Maxon Motor). The editor presents an overview of all motor characteristics and can be used to select a motor and test the performance of the motor in a model.

More details on 20-Sim can be found on the website (20-Sim, 2005).

## 1.2 Previous work

This project is a follow-up of two earlier projects. A short introduction to these projects will be presented in the following sections. Parts that are related to this project will be explained more thoroughly.

The main result of the first project (Groothuis, 2004) was a “HIL simulation demonstration setup” which is used in this project. A disadvantage of this setup was its ease of use. To be able to use the setup, a lot of knowledge of the setup was needed. In order to make the setup more user friendly a second project was started. The main result of this project (Buit, 2005) was a tool chain. This tool chain provides a user interface to make the connection between a model made in 20-Sim and real hardware. The next two sections will describe these two projects in more detail.

### 1.2.1 Distributed HIL simulation of Boderc

#### Architecture

Figure 2 shows the architecture of the setup that was proposed and later on realized.

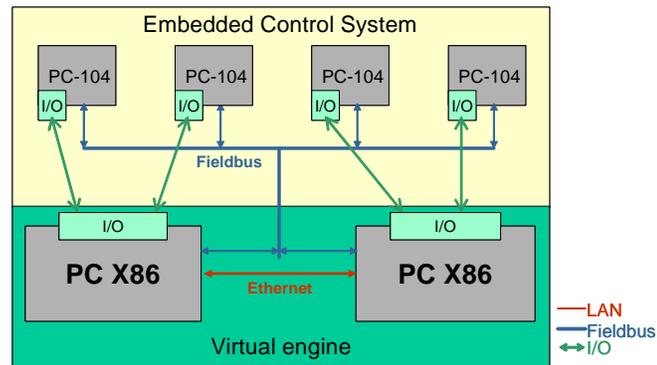


Figure 2 – Architecture of the proposed setup (Groothuis, 2004)

In this figure the PC-104 blocks are Embedded Stacks (EST). An EST consists of a processor board, a CAN interface and an I/O interface print called Anything IO. The PC X86 blocks are the simulation PCs (SPC). These SPCs are common of the shelf (COTS) PCs with three extension cards. These card are the normal PCI version of the Anything IO card, the CAN card and an extra Ethernet controller. On both the EST and the PC X86 Linux is used as operating system. The Linux operating system is build from scratch and only the necessary modules and tools where added to keep it as small as possible. Also special modules where added to increase real-time performance.

### Anything IO

The Anything IO board of the EST is developed by Mesa (Mesa Electronics, 2005). The Anything IO board contains 3 connectors with each 24 I/O pins. The I/O pins can be used as general input or output. This card is connected to the PCI bus of the processor board and takes care of the connection to the hardware. It contains a Xilinx FPGA (Field Programmable Gate Array) which makes the design very flexible. Several configurations where made to provide the right type of I/O to connect the HIL simulation demonstration setup (which will be addressed later on). Also a special driver was made to make it possible to address the Anything IO card directly or via the kernel space of Linux.

### CAN

The CAN interface card is another feature of the setup. This field bus is used for communication between the ESTs and even for a distributed control loop with at least two ESTs. Therefore it is important that the CAN bus is fast enough to keep up with the real-time requirements. To make sure this was the case, several test where done to check the speed of the bus.

### HIL simulation demonstration setup

To demonstrate de correct working of the setup a demonstration setup was created. Figure 3 is a schematic representation of this setup.

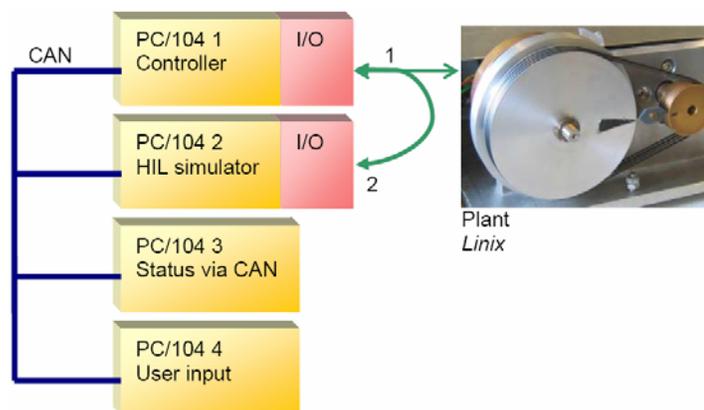


Figure 3 – HIL simulation demonstration setup (Groothuis, 2004)

In this figure the first EST is used as a controller, the second as a HIL simulator, the third displays status information and the fourth handles user input. The ESTs are connected through CAN to demonstrate the correct working of the CAN bus as well. On the right there is a real plant called Linux which was already present at the Control Engineering group. A model of this plant is located in the HIL simulator. There where two possible connections. To connect the controller to the real plant (1) or the HIL simulator (2). With this setup several test where done and they showed that the whole setup was working well.

### 1.2.2 PC104 stack mechatronic control platform

This section gives a short impression of the work that was done by Erik Buit in a project called “PC104 stack mechatronic control platform”. The goal of this project was to present a general method to deploy a task on a embedded device. The next sections describe the main aspects of this project.

#### MSCT overview

Figure 4 gives an overview of the Mechatronic Stack Connection Tools (MSCT) involved in the generation of code and the deployment to a target platform.

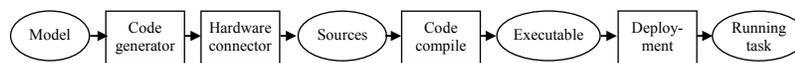


Figure 4 - Transformation process (Buit, 2005)

First the modeling tool generates code from the model. Then the hardware connector is started in which the user connects the hardware to the model. After this, a tool called compiler assistant is started which compiles the code with the right compiler and flags for a specified target. When the code it generated a tool called deployment manager is started which upload, start and stops the task on the target platform. All the configuration options for these tools are stored in XML format.

#### Command and Control Environment

The Command and Control Environment (CCE) consist of a set of tools that could be used to control the target. With the command line tools of the CCE, task can be started, stopped or restarted. Also the CCE makes it possible to view and change parameters. Another feature of the CCE is the synchronize start of multiple target. Currently this is only implemented for a CAN bus. Also the CCE uses a stack demon on the target platform which is currently only implemented for platforms that use Linux as an operating system.

#### Embedded stack and demonstration setup

The test case for this project was the early described “HIL simulation setup”. Next to the implementation of the mentions tools and stack demon also small alterations where made to the Linux modules and file system running on the embedded stacks. Also special configurations for the anything IO card where made to make the test possible. The tests showed that the complete environment was working as planned.

### 1.3 Project description

#### Mechanical setup

The main goal of this project is to create a mechanical setup for the earlier described “HIL simulation setup”. This mechanical setup will be used in the Boderc project to validate there theories and therefore should satisfy their needs. As earlier described, they use a large Océ printer as a test case. This is a high velocity printer which prints A4 sheets at approximately 60 pages per second (pps). The mechanical setup will represent a part of this copier, to be more specific, a part of the paperpath of this copier. The meaning of the term paperpath is explained in the next chapter. Important aspects of the mechanical are:

- Realistic, key features of a high velocity printer should be present.

- Surplus, sufficient actuators and sensors should be present to test different scenarios.
- Flexible, placement of actuator and sensors should be variable.
- Controlable, capable of testing several control scenarios (normal and distributed).
- Insightful, because it is a demonstration setup interesting aspects of the setup should be visible.

Next to the creation of a mechanical setup there are some other aspects to consider. These aspects are stated in the next sections

### **Interfacing**

The mechanical setup will be connected to the already existing embedded stacks (EST). To make this possible, an electrical interface should be developed. This interface should make it possible to connect the actuators and sensors in a flexible manner to the anything IO card of the ESTs. Also new configurations for the anything IO card should be developed. These configurations are necessary to be able to control all the actuators and sensors.

In the remainder of this thesis the mechanical setup with the interface will be called “paperpath simulation setup” or PASS

### **Integration**

This will be the third project that uses the same ESTs. This has led to a setup with several different installations and anything IO configurations. If possible, it would be nice if there is a platform developed which makes it possible to operate the PASS and still be able to run the demonstrations of the previous projects. This platform should have just one installation and a few, good organized, anything IO configurations.

### **Experiments**

At the end of the project experiments should be performed to validate the correct working of the setup. These experiments include unit testing and integration testing. The experiments results should be validated with the requirements.

## **1.4 Report outline**

The second chapter describes the global architecture of the mechatronic setup. The chapter starts with an introduction on all aspect off the setup. After this the requirements are described which are followed by the design choices. At the end of the chapter the global architecture of the PASS is introduced.

The third chapter describes the mechanical and electrical design of the PASS. The chapter starts with the design choices and details of the mechanical part of the design. This is followed by the design choices and details of the electrical part. The chapter ends with an overview of the total PASS.

The fourth chapter describes the interfacing of the setup to the ESTs. The chapter starts with an introduction on the software architecture of the ESTs. This is followed by the FPGA design.

The fifth chapter describes the experiments that were performed to validate the mechatronic setup. This includes the results and comparison with the requirements. The chapter starts with fundamental experiments. This is followed by experiments on the integrated setup. The chapter ends with the description of the calibration method.

The sixth chapter describes the conclusions and recommendations.



## 2 Global Architecture

This chapter describes the global design of the complete setup. This will include the PASS and the ESTs. In the remainder of this thesis the complete setup will be called Mechatronic Simulation Setup or MESS. First the different applications are described. They will be converted towards requirements. These requirements will be split up towards the different aspect of the MESS. Also a global design will be presented. This will give an overview of the total design.

### 2.1 Introduction to the MESS

This section gives a short introduction in the complete system. This will make it easier to understand the used terms. The first section will explain the main aspect of the PASS. The second section will show how this all fit together in the complete MESS.

#### 2.1.1 Aspects of the PASS

##### Paperpath

The term paperpath is used to describe the path that the paper travels through a copier. This is the complete path from the input to the output of paper. The term also includes the drive system to transport the paper through this paperpath. Figure 5 is an example of a paperpath in a copier.

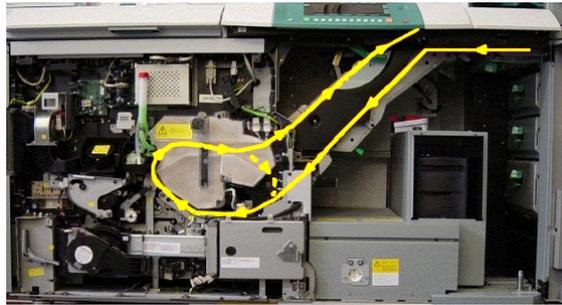


Figure 5 - Paperpath of a copier

A critical point in the paperpath is the fuse pinch. This is the point in the copier where the image is printed onto the paper sheets. At this point it is crucial that the image and the paper sheet meet each other at precisely the right time or the image will be misplaced. For instance, at 100 pages per minute (PPM) and 50 mm space between pages a delay of 1 ms will shift the image approximately 0,5 mm. Sensor and actuators are used to minimize the misplacement of the image.

In this project there are three key parts of the paperpath namely a pinch, the paper input module (PIM) and the sheet detectors. These parts are described in the next sections.

##### Pinch

The pinch is the part that drives the paper. It consists of two rollers which are pinched together with springs. A motor drives these rollers directly, via cogs or a drive belt. In some cases two or more pinches are connected together via a drive belt which is driven by a single motor. The way the pinches are driven, including the transmission, is called a drive system or drive.

##### PIM

The paper input module (PIM) is where the paper is fed into the copier. The PIM removes one paper sheet of the paper stack and speeds up the paper sheet. This is a critical aspect of the paperpath. It is important that only one paper is fed each time. Other aspects are the inter sheet distance and the skew of the paper. The inter sheet distance of the paper is the space between two succeeding pages. The skew of the paper is the angle of the paper that it deviates from the normal orientation.

## Sheet detectors

A sheet detector is a light sensor that gives a signal when a paper sheet passes the sensor. These sheet detectors are placed throughout the paperpath to keep track of the paper sheets as they move along the paperpath.

## Interfacing

The sensors and actuators of the PASS will be connected to the Anything IO boards of the ESTs. The sensors and actuators cannot be connected directly to the Anything IO board. Therefore an interface is needed which has three functions. The interface connects the individual actuators and sensors to the Anything IO board. Secondly, the interface delivers the power to the actuators and the sensors. Thirdly, the interface protects the sensors and Anything IO board. This protection is needed because the FPGA on the Anything IO board can be programmed in any way. When the FPGA is programmed wrong a sensor output could be connected to an output port of the FPGA. This could damage either the FPGA or the sensor.

## PASS

As earlier described the paperpath simulation setup (PASS) represents a part of the paperpath. In a copier this paperpath is not visible and complex. Paper sheets move through the complete machine and sometimes even loop back to print the other side. The PASS is a simplification of the paperpath. It is a small straight paperpath which consists of a PIM, several pinches, sheet detectors and an output tray. Also the paper sheets should be in sight most of the time. Figure 6 is a schematic representation of a possible PASS. This is only the mechanical part, the interface is left out.

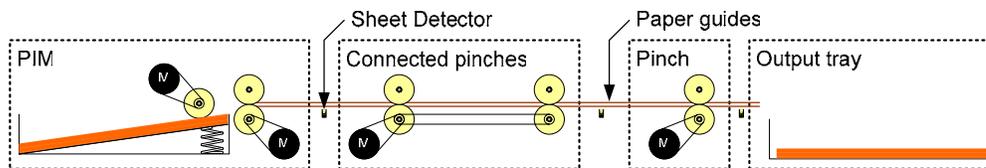


Figure 6 - Example mechanical part of the PASS

### 2.1.2 Overview of MESS

This section will give an overview of the MESS and the link to earlier projects. Figure 7 is a schematic representation of the MESS. It is an extension of Figure 2.

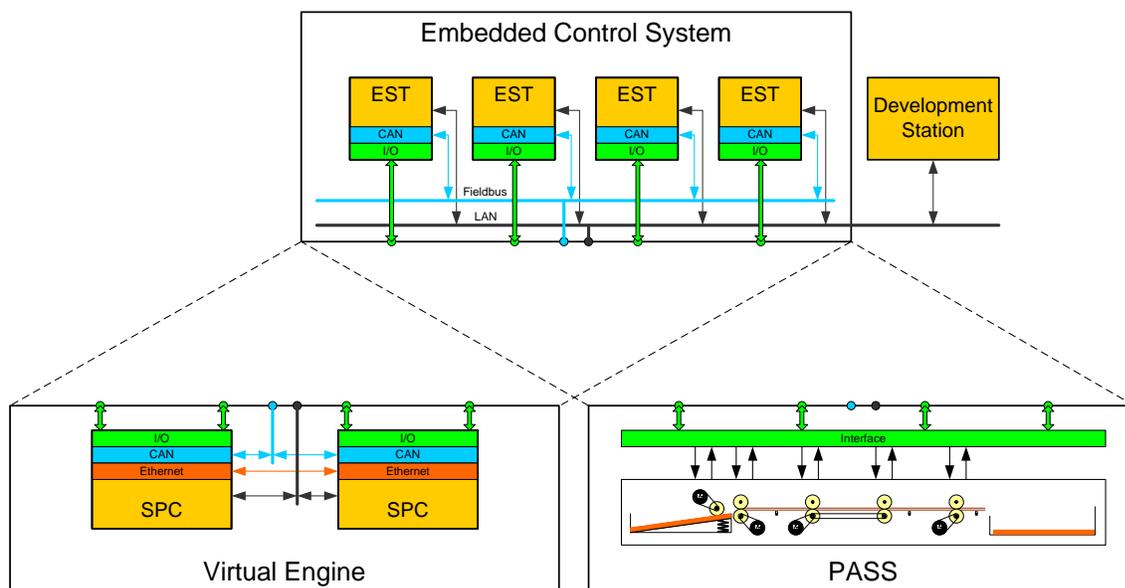


Figure 7 - Schematic representation of the MESS

The Embedded Control System (ECS) and the Virtual Engine (VE) are almost the same as the one described in chapter 1. The LAN connection is the only difference in these two blocks. This bus connects the ESTs and SPCs to the Development Station. Here the controller and the models for the Virtual Engine are designed. After the model and the controller are designed they can be deployed using the hardware connector tool which is also described in chapter 1. The new part is the PASS. The Virtual Engine and the PASS are interchangeable. This way the HIL simulations can easily be performed and verified. The Embedded Control System, the Development Station and the Virtual Engine were already present. Only small alterations to the installation are necessary to make it suitable for this project. The PASS and the interfacing of the PASS are newly developed.

## 2.2 Requirements

As described in the previous section, the only complete new part is the PASS. This is why the requirement analysis is only done for these parts of the MESS.

### 2.2.1 Application areas

The MESS will be used in a group which is part of the Boderc project. The group will use the MESS as a prove of concept of hardware in the loop simulation. During experiments several control architecture will be tested.

The setup will be used as a demonstration setup at the university. This will have no impact on the design decisions.

Only the needs from the Boderc project influence the complexity of the MESS. Therefore during the extraction of the requirement and during the whole design only this application drives the decisions.

### 2.2.2 Application experiments

The experiments that will be performed in the Boderc project determine the characteristics of the MESS. The experiments are used to determine the requirements of the MESS. These experiments will not be performed within the time-span of this project.

First a list of experiments that the MESS should be able to perform without making any major changes:

1. Emulating part of a realistic paperpath with a single controller.
2. Emulating part of a realistic paperpath with a distributed controller.
3. Test the influence of the number of sensors. Determine the minimal amount of sensors, the optimal amount of sensors and the maximum amount of sensors. The maximum amount of sensors is reached when additions of sensors leads to a decreases in performance.
4. Test the influence of the connections of sensors and actuators to the controllers. For instance, use a sheet detector near to an earlier pinch to control an actuator.
5. Test the influence of the number of motors connected to 1 controller.
6. Test the influence of the connections of the sensors to the controllers. For instance, test if it is possible to connect all sheet detectors to 1 controller. Or switch the connection of the sheet detectors of two pinches
7. Test the influence of the placement of the sensors. For instance, test the minimal, optimal and maximal distance between the sheet detectors and the pinches.
8. Test the use of different types of motors. For instance a more / less powerful motor, a DC motor or a stepper motor.
9. Test impact on longer running times. Determine if the longer running affect the setup.

Secondly a list of experiments that could be nice to perform but are not really necessary:

10. Test the transportation of larger paper. This way the paper is present in more than two pinches at ones.
11. Test the influence of the placement of the pinches.
12. Test the influence of the placement of the motors (direct or belt driven).
13. Test impact of the insertion of paper under an angle.

Next to these experiments there is another aspects to consider. As stated before, the setup is part of a HIL simulation. Therefore it should be easy to connect and disconnect the PASS from the ECS. In the Boderc project the MESS is used at different locations. Therefore it is required that the MESS must fit inside a “normal” car. This limits the maximum size and weight of the PASS.

### 2.2.3 Characteristics summary

All the experiments of the previous section were analyzed to determine the impact they had on characteristics of the PASS and interface. The complete analysis is added as Appendix I. Table 1 gives a summary of the characteristics. The table also includes a rating for each characteristic. This rating is a combination of the importance of the characteristic and the impact it has on design decisions.

Characteristic	Value	Importance for design				
		1	2	3	4	5
<b>Mechanical</b>						
<b>Pinches</b>						
Minimal number of pinches	3					X
Variable pinch placement	?					X
<b>Pinch drives</b>						
Minimal number of drive systems	3				X	
Flexible motor mounting	X					X
Direct driven	?			X		
Belt driven	X			X		
Pinches connected (belt)	-	X				
<b>Sensors</b>						
Minimal number of encoders	4			X		
Minimal number of sheet detectors	12			X		
Variable placement of sheet detectors	X					X
<b>PIM</b>						
Minimal number of sheets	200					X
Variable skew	?			X		
Variable size of sheets	?			X		
Smallest inter sheet distance of paper (mm)	10			X		
Maximum inter sheet distance of paper (mm)	50			X		
<b>Interfacing</b>						
Flexible connections	X					X
<b>Performance</b>						
Pages per minute (PPM)	100				X	
Maximum acceleration (m/s <sup>2</sup> )	49				X	
<b>Dimensions</b>						
<b>Size</b>						
Maximum width	150 cm			X		
Maximum depth	50 cm			X		
Maximum height	40 cm					X
Maximum weight	70kg			X		
<b>Costs</b>						
	-					
*X* Characteristic that is needed for basic functionality / Selected column						
*?* Characteristic that is optional						
*-* Characteristic that is not important						

Table 1 - Characteristics summary

Details on this table can be found in the next section and in Appendix I.

## 2.3 Global design choices

This section describes the decisions that were made to determine the global architecture off the PASS. Decisions on main features were made in co-operation with the Boderc group to ensure a result that is desirable.

Some parts of the PASS are provided by Océ. These parts are from a copier that is already in production. Using parts from a real copier makes the PASS more realistic and reduces the costs. The parts that are provided by Océ are described in the chapter about mechanical design.

## Pinches

There are three design aspects which are related to the pinches. These are the number of pinches, the variable placement of pinches and the drive system.

To be able to simulate a realistic part of a paperpath at least three pinches are needed. The number of pinches affects the size and complexity of the PASS and the number of actuator and sensors that are needed. There is decided to use four pinches for the PASS. Four pinches can be placed within the maximum dimension and it is enough to represent a realistic part of a paperpath. One of these pinches is part of the PIM and speeds up the paper. Another is positioned at the end and will have a constant speed which simulates fuse pinch. This leaves two pinches that can be used to for the precise positioning of the paper sheets. All pinches need to be controlled and influence the complete controller design.

The variable placement of the pinches means that the distance between two pinches can be changed. The variable placement of pinches is optional and is left as a mechanical design decision.

The third aspect is the pinch drive. To be able to test different types of motors there is decided on a flexible way to mount the motors. This makes it easy to switch from one to another type of motor. This type of mounting is easier when the pinch is driven with a belt drive. Therefore the decision was made to use only belt driven pinches. Also the possibility for the two connected pinches is discarded. As a result is each pinch belt driven with each its own motor.

## Sensors

The setup will contain at least two types of sensors, sheet detectors and quadrature encoders. Sheet detectors are light sensors that are used to detect the presence of a paper sheet. Quadrature encoders are mounted on an axle and measure the rotation of the axle. There are three design choices related to the sensors. These are the number of sheet detectors, the variable placement of sheet detectors and the number of quadrature sensors.

On an experimental setup, such as the PASS, it is good to have a lot of sensors to retrieve sufficient data on each experiment. Next to this, the number of sensors that are needed for control is one of the tests that will be performed. For this test at least 12 sheet detectors are needed. The sheet detectors will be placed near each pinch. A pair of sheet detectors will be placed just before and just after each pinch (within 2 cm). Another test that is performed is to test the impact of the position of the sheet detectors. Therefore the place of each sheet detector must be easy to change.

The quadrature encoders are connected to the axles of the motors. Each motor will contain a quadrature encoder.

In normal operation the sheet detectors are also used to determine the skew of the paper sheets. If the positions of the sheet detectors are known, the time difference of two sensors is enough to determine the skew. This is not the case. As mentioned earlier the position of the sensor may be changed. Also the placement of the sensor cannot be measured precise enough to give accurate values of the skew. To solve this problem, three possibilities were investigated. These possibilities are using three sensors on a row, using a calibration sheet with a known angle on one site or an array sensor. The first two cases resulted in the same problem. It is not possible to determine the skew without knowing the position of the sensors in respect to one another. Solving this problem with an array sensor is possible. Therefore the choice was made to use an array sensor.

An array sensor is an IC which consists of a number of light sensors placed in a line. For instance more than 100 sensors with a distance between the centers less than 100  $\mu\text{m}$ . The detected amount of light of each sensor can be read independently. The array sensor can be used to detect the area of the sensors that is covered with high precision. This sensor is placed on the edge of the paperpath. Because of the large amount of data from the sensor this sensor is only used in the calibration phase. When the angle

of the paper is known, the position of the sheet detectors can be determined. After this the sheet detectors can be used to determine the skew.

### PIM

The main characteristic of the PIM is the number of sheets it may contain. The minimal require amount is 200. To limit the complexity and weight the maximum number of pages is decided on 300. The precise amount is left as a mechanical design decision. This amount of pages limits the continuous run time. At full speed the runtime will lie between the 2 and 3 minutes. When longer test are required, lower speeds will have to be used. Or “dry run” while emptying the output tray and filling the input tray.

The option of variable skew and use of different sized paper is left as a mechanical design decision.

### Interfacing

The requirement of the interfacing is the flexible connection. Choices related to the interfacing are made in section 3.2. Here the electrical part of the PASS is described in detail.

### Performance

The performance of the PASS influences the design. The performance has a great impact in the choice of the motor. The PIM and output tray must also be able to handle paper sheets at the required speed. The required speed by the Boderc project is 60 Pages Per Minute (PPM). To be able to perform future experiments the choice was made to design the PASS to be able to operating up to 100 PPM. During the mechanical design these requirement should included in design decisions.

### Dimensions

The dimensions are limited by the requirement that is must be possible to transport the MESS in a “normal” car. The dimensions in Table 1 are an estimation of the maximum dimension. When the setup is within these boundaries it is possible to fit the PASS and the other components of the MESS in a car. The maximum weight is related to the weight that two people can carry. Because the PASS should be quite stiff the weight might reach its limit and therefore influences design choices. During the mechanical design these requirement should included in design decisions.

### Costs

The budget for this project was estimated for an out-door production but will be produced in-house. Because of this the limitation of the costs are not an important design aspect. When a decision does not influence the performance the cost will be the decisive factor to keep the costs low.

## 2.4 Global architecture off the PASS

This section describes the global architecture of the PASS and the interface.

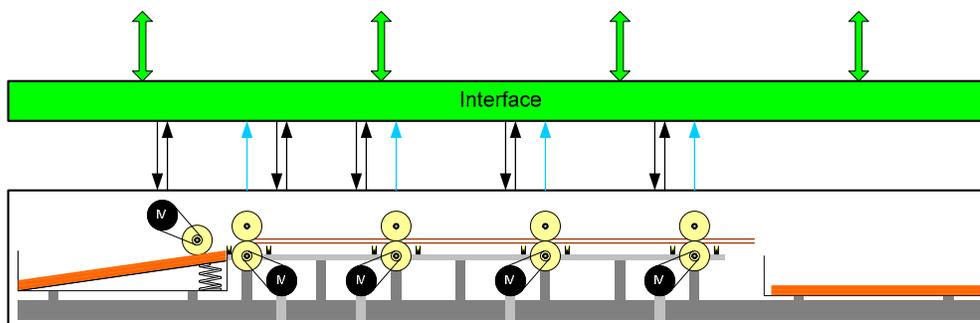


Figure 8 - Global architecture PASS and interface

Figure 8 is a schematic representation of the global architecture. All the decisions described in section 2.3 are represented here. There are four pinches with each its own belt driven motor. The PIM has an

extra motor to transport a paper to the first pinch. Before and after each pinch a sheet detector is drawn. Each sheet detector represents two sheet detectors placed next to each other. Everything is connected to a frame. The position of light bars which connect the motor and the sheet detectors to the frame are easy to change. The arrows between the PASS and interface are the signals from the sensors and to the actuators. The interface takes care of the flexible connections to the EST, the protection of the components and the power supply of the sensors and actuators.



### 3 Mechanical and electrical design

This chapter describes the mechanical and electrical part of the PASS.

#### 3.1 Mechanical

This section describes the mechanical construction of the PASS. The first section describes the choices that were made to reach a basic layout. The second section will go into more detail about the design of specific part. The last section describes the construction and the result.

##### 3.1.1 Design choices

To reduce development time, the modeling of the dynamic behavior of the complete PASS was not performed. Only a model to assist in the motor and gear choices was developed. The other design choices were made on practical experience with the consultation of experienced constructors. These decisions are described in this section.

##### Océ parts

As mentioned earlier a number of parts are provided by Océ. A disadvantage of using these parts is the limitation of the design freedom. The parts already give a fixed width to the setup and have specific way to mount all the parts. An advantage is the fact that they already exists. They are already tested thoroughly and are ready to use which saves a lot of time. A supplementary advantage is reduction of the costs.

The components that were supplied by Océ are almost all part of the pinches, they are:

- Bottom roller – An axle with two rollers that drives the paper.
- Top roller – Smaller axle with roller that only presses the paper onto the bottom roller.
- Roller mounts – Mount where the bottom rollers fit in and can easily be connected to the frame.
- The pulleys – Connects a motor or roller axle to a drive belt.
- The drive belts – Connects the pulleys of a motor and roller axle together.
- Conducting brushes – Discharges the roller axle to the frame (roller mount are from plastic).
- Paper detectors – The earlier described paper detectors. Only component that is not part of a pinch.

These parts are all used in the realization of the PASS.

##### Pinches

The pinches have a large impact on the design. The pinches determine the dimensions of the complete design. One aspect is the width of the rollers. They determine the width of the mechanical part of the PASS. Another aspect is the diameter of the rollers. The distance between two pinches is chosen to be a multiple of the circumference. Using such a distance makes it easier to have an indication of the position of a paper sheet. This is only an indication because of the high precision of the sensors. The sensors are capable of detecting displacements even below 100 micrometer. In the mechanical construction it is nearly impossible to reach this precision. Therefore it is only used as a guideline. Another aspect is the size of the paper. A paper sheet should always be present in at least one pinch. As earlier described an A4 paper is used with a landscape orientation. This leads to a maximum distance between two pinches of 21,0 mm. The circumference of the rollers is 87,3 mm. Two times this value leads to a pinch distance around 175,0 mm.

##### Base

One of the decisions was the choice of the base of the design. This base must be very rigid but not too heavy. Furthermore it should be easy to mount the other part on the base. Because of the size of the setup a solid base is not an option. These limitations led to the choice of using aluminium profiles. Figure 9 is an example of the type of profiles that are used.



Figure 9 - Profile example

These profiles have a number of advantages. There are a lot of different components available for these profiles. This makes it easy to build a base and has the advantage of being extendable. The hollow design makes the profiles lightweight in comparison to their stiffness. Another advantage is the ease with which other parts can be mounted to the profiles. The profiles are produced in several different diameters. The forces that the profiles has to endure must be assessed to determine the needed with. The pinches and the paper sheets are the only moving parts that deliver force. Because of the small masses of these moving parts the forces are small. Forces as a result of the weight of the pass are higher than the forces produced by the moving parts. The forces generated by the moving parts are in the order of 1 N. The forces as a result of the weight are in the order of 100 N. Another aspect to consider are the vibrations that occur by controlling with high velocities and accelerations. To cope with these vibrations the frame must be stiff. According to the specs of the profiles the smallest version is strong enough to cope with the described forces and vibrations. This profile is 20 mm in diameter. A disadvantage is the limited number of components that are available for the smallest profile. Another disadvantage is the small contact area of this profile. This could result in play between the mounted parts and the profile. Play leads to vibrations in the parts. To prevent this play a bigger profile (30 mm) is used for the design. It is stronger and has greater connection surface. A disadvantage is the increase in weight. With the same length the weight of the profile is doubled but this stays within the limits of the maximum weight. A bigger profile is not needed and would again double the weight of the base.

### Motor and gear selection

The selection of the motor is an important aspect in the design choices. When the motors are not powerful enough the requirements of speed and acceleration will not be met. A powerful motor will increase the cost of the motor, amplifiers and power source. Therefore a motor must be chosen that is capable of reaching the requirements without being too powerful. This section describes the choices that were made based on the simulations. The simulations and results can be found in Appendix II

After the motor choice the gearing is determined. The choices for the motor and the gearing were made based on simulations result. 20-Sim was used to make the model and run a number of simulations. The model that was used for these simulations is shown in Figure 10.

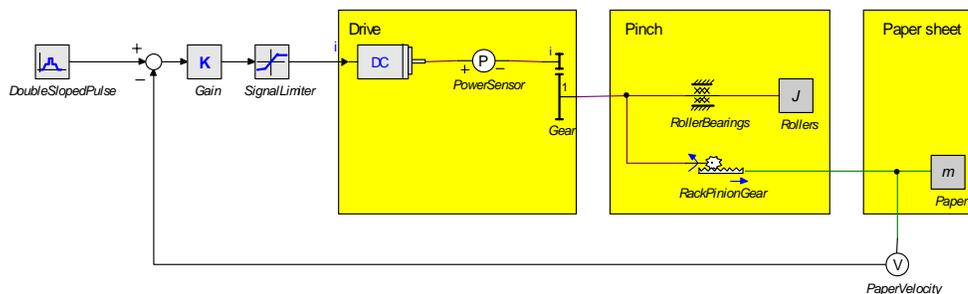


Figure 10 - Simplified pinch model

The goal of these simulations is to determine the right type of motor with a certain amount of gearing. Therefore the model is simplified to represent the dominant aspects. For the simulations a basic controller is used. The controller uses velocity feedback with a gain controller. This controller is adequate because only an estimation of the needed power and gearing is made. The model is tested

with the minimal required speed and acceleration. This is done by applying a double sloped pulse generator. This pulse generator first accelerates to half the maximum speed and after a short interval to the full speed. The second time the maximal acceleration is used. The signal from the gain controller is limited to simulate clipping of the motor amplifier. After this the drive is placed. The drive consists of a motor with gearing. On the mechanical site of the motor a power sensor is placed. This sensor is used to give an estimation on the minimal required power. The drive drives the pinch. The parameters of the pinch are all duplicated. This mimics the situation that a paper is still in the previous pinch and one motor has to drive two pinches. The roller inertia is calculation from its weight and diameter. The roller bearing resistance was unknown, therefore this value is estimated. Experience from Océ showed that the impact of bearing resistance is minimal. The most power is used for the acceleration of the rollers. With this in mind the roller resistance was estimated by simulation. An ideal rack-pinion-gear is used to model the paper-roller contact. Appendix II contains all the measurements, calculations, parameters and simulation results that are relevant to the motor and gear selection.

The motor choice was made with the help of the 20-Sim Servo Motor Editor which is described in the first chapter. The Servo Motor Editor contains detailed motor models from the stock program of Maxon motors. The detailed model of the motor makes it more suitable to use in HIL simulations than motor with less accurate characteristic data. Another advantage is the short delivery time and good support. A disadvantage is the relative high price. Because of there high precision and reliability the price is higher than that of motors of the competition.

First the bearing resistance was estimated. After this simulation were performed to determine the minimal power rating of motor. This was deduced by simulating without gearing and with the earlier described motion profile. The peak use lays around 1.5 Watts. Motors that are used at Océ for similar high velocity printers are around 50 Watts. Based on these findings the following motors were used for the remainder of the simulations:

- Maxon RE25 10W
- Maxon RE25 20W
- Maxon RE30 60W

All motors have a working area. This is an area with a certain speed and force in which the motor is designed to operate. In most applications the required speed and torque are not in this area. When this is the case gearing needed. This is the case in this application. The speed of the rollers is lower than the speed of the working area. To compare different motors and gearing, a torque speed plot was used. An example of this plot is shown in Figure 11 which is followed by a short explanation.

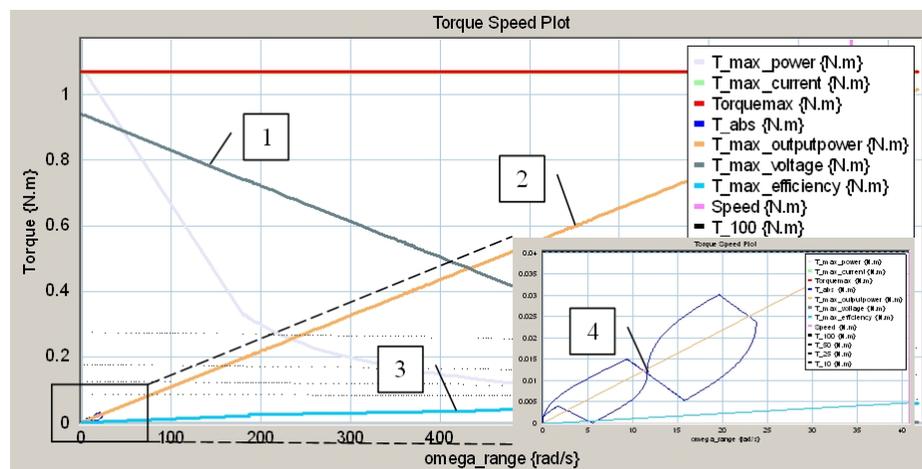


Figure 11 - Example torque speed plot

Relevant lines of these plots are:

1.  $T_{\max\_voltage}$
2.  $T_{\max\_outputpower}$
3.  $T_{\max\_efficiency}$
4. Experiment line

When the motor is in use, it is best that the motor is in the operating area. This is the area between the lines 1, 2 and 3. In this picture it can be seen that the experiment only uses a fraction of the motors working area. The experiment even exceeds the  $T_{max\_outputpower}$  – line (clearly shown in the magnification). The example plot is the result of an experiment with the earlier described model and the Maxon 60 Watt Motor. This indicates that the 60 Watt motor needs some kind of gearing. The other two motors are designed to deliver less torque and therefore need some gearing as well. To determine the amount of gearing that is best, the 20-sim optimization tool was used. The optimization was done by sweeping the gear from ratio 1 to 1/100. The Integral Square Value method was used with the steer signal as input. This signal can be used as a representation of the amount of power that is needed. The Integral Square Value method was chosen for an extra penalty on high steer signals. The optimization technique was performed for all three motors. The results of this optimization are shown in Table 2.

Motor Type	Optimal gear
Maxon RE25 10W	0,10
Maxon RE25 20W	0,10
Maxon RE30 60W	0,16

Table 2 - Optimization results

The motors are connected to the rollers by the earlier described belts and pulleys which are supplied by Océ. The size difference of the motor pulley and the roller pulley give a transmission of 18/37 ( $\approx 0.486$ ). Simulations with this gearing showed that even the 10 Watt motor will reach the requirements. This indicates that the 60 Watt motor is much too powerful and therefore not suitable for this application. The simulations indicated that the performance of the 10 and 20 Watt motors do not differ much in there response. To be on the save side the 20 Watt motor seems the right choice for this application. Still extra gearing is needed to place the normal operation of the motors in the working area of the motor. A disadvantage of the extra gearing is the negative effect the characteristics of the gearing have on the behavior of the model. Most type op gearboxes have play, extra resistance and inertia. Especially the play is difficult to model. That is why four of the five motors do not have extra gearing. To be able to test the effect of gearing, one motor has a gearbox. This gearbox has a gear ratio of 5/24. The belt transmission and gearbox together give a total transmission of 90/888 ( $\approx 0.101$ )

### 3.1.2 Detailed Design

This section describes the design in more detail. First an overview of the mechanical part of the PASS will be presented. This is followed by details and choices about the sub-designs. Most measurements and detailed drawings of the sub-design are left out. They can be found in Appendix III.

#### Complete design

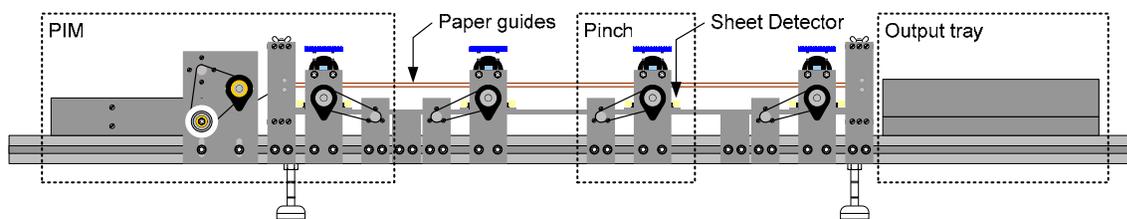


Figure 12 - Detailed drawing of the mechanical part of the PASS

Figure 12 is a detailed drawing of the PASS. In this figure all earlier mentioned parts are visible. As early described the PIM includes one pinch. This pinch is the same as they others and therefore will not be mention in the explanation about the PIM.

#### General

One requirement is the weight of the design. To keep the design as light as possible aluminum was used where possible. Only materials that differ from aluminum will be explicitly mentioned in the next sections.

## Base

The base of the PASS is a framework of profiles. This framework consists of two main bars which are connected by three crossbars. The whole base is placed on four feet to leave room for the bottom plate and provide a steady base.

## Pinches

The pinch consists of two parts, the roller part and the motor part.

The roller part consists of a bottom roller and a top roller. The bottom roller is mounted with two roller mount to plates that are connected to the frame. The top roller part is smaller and has a specific connection which need a clasp fix. Because this part is on top, it blocks the view of the paperpath. To keep the paperpath as visible as possible the mount for this part is made of plexiglass. This could lead to some problems with static electricity but there is enough space between the paper sheets and the plexiglass.

The motor is mounted separate from the rollers. This way it is easy to change from one type of motor to another. Another advantage is the easy with which the drive belt can be tightened.

Another aspect was the variable pinch placement. Because profiles are used this is automatically possible. All parts mounted on the profiles can be shifted sideways.

## PIM

The design of the PIM is kept as basic as possible. If experiments on the working of the PASS show that there are problems with the PIM it needs to be redesigned. The PIM can also be divided into two parts, the paper tray and the drive system. A top and side view of the paper tray and a side view of the drive system are presented Figure 13.

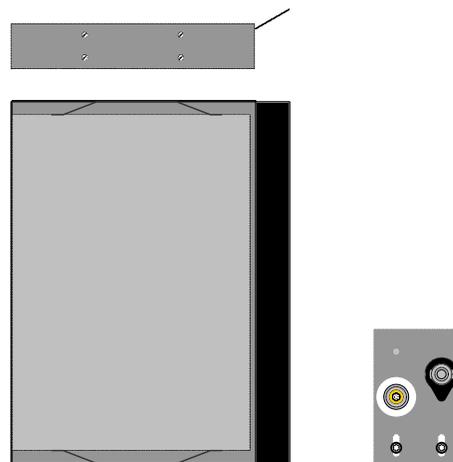


Figure 13 - Input tray

Because of its complexity the PIM is explained in more detail. Figure 13 shows the detailed drawing of the paper barge. The whole barge is made of RVS. This is done because it is easier to weld and it is stiff for thin material. The light plate in the bottom of the drawing is a plate with the same dimensions of a paper sheet. Below the plate there are two springs which presses this plate (and thus the paper sheets) up against the roller. This can also be seen in the top part of the drawing. On the two short sides there are spring plates which keep the paper sheets aligned. The sloped plate on the right guides the paper sheets in between the paper guides. There is a rubber layer placed on the sloped plate to reduce the chance that more than one sheet is transported into the paperpath. At the moment Crepla rubber is used because it was available. Other types of rubber might work better. Tests of different types of rubber for paper tray are described in (Suzuki et al., 1998).

The drive system, in contrast to the pinches, is connected on the same plate as the roller. The plates for the roller and the motor are connected directly to the frame. The connection to the frame is adjustable. This way the roller can be placed higher or lower depending on the desired height.

Other aspects of the PIM are the angled input and the variable size. Because profiles are used this can be implemented. The paper tray can be adjusted so it can pivot around one corner creating an angled input. By designing a second paper tray, different sized paper could be used. If the height is the same the drive system does not need changes.

### **Output paper tray**

The output paper tray is a straight forward tray. The tray consists of a bottom plate with a u-shaped edge of 40 mm high. The open design makes it easy to take out the paper sheets. As a result of the limited time span the output tray is now made of carton. The output tray should be constructed from RVS.

### **Paper guides**

The paper guides consists of six copper threads which guide the paper through the PASS. At the beginning and the end each thread is wrapped around a fixed to a screw-eye. These screw-eyes can be raised to tighten the threads.

### **Sheet detector mounts**

The placement of the sheet detectors should be variable. To make that possible there are two bars placed perpendicular and beneath the rollers. These bars have holes at every 10 mm. On this plates with each two sensors are placed near the pinches. These plates have two holes for each bar spaced 5 mm apart. By using one of the two holes the plates can be placed every 5 mm.

### **Array sensor mounts**

The array sensor mounts are not jet constructed. This is because of the limited time span. Because the sensor is lightweight the sensor mount can be very small. Special attention is needed to reduce the amount of environment light that enters the sensor.

### **Bottom plate**

The bottom plate consists of a RVS plate that slide across two guides. These guides are suspended beneath the profiles.

## **3.1.3 Construction & Result**

This section only describes some point of attention during construction. These attention points surfaced during the construction of the mechanical PASS. The complete description on the construction is included as Appendix III.

### **Construction**

Attention points:

- Thickness of materials is not always constant. Especially not from plexiglas. For some components this could be a problem.
- Measurements should always be carried out from one side. This way measurements errors are kept to a minimal. When to plate are mounted across from each other the side from which is measured should be mirrored.

### **Result**

The constructed mechanical PASS is 120 cm by 40 cm and 21 cm high. The PASS weights about 14 kilograms. The setup has 4 pinches of which one is part of the PIM. There are five identical motor which drive the pinches and the PIM. These motors can easily be replaced by a different type of motor. The motor connected to the PIM has extra gearing. A quadrature encoder is attached to each motor. 16 paired sheet detectors are connected to a flexible frame. The paper guides are made of copper threads to keep the paper visible. The PIM and output tray can contain 250 paper sheets.

## 3.2 Electrical

This section describes the interface part of the PASS. The main feature of the interface is its flexibility. The interface must be able to perform all tests that are described in section 2.2.2. The first section describe the decisions that where made to reach a general solution. After this the choices that were made and the design itself is described. At they end there is a short section about the implementation of the interface.

### 3.2.1 Design choices

To be able to design an interface an inventory is needed of all the signals and connectors. After this scenarios are introduced. These scenarios provide a platform for the tests. After the scenarios the general solution is elaborated.

#### Interface analysis

As earlier described the PASS will be connected to an embedded controller which consists of four EST. These EST have each three connector which consists of 24 input / output signals. Each connector is intended for a 50 pins flat-cable. To make it easy to use different ESTs these flat cables are used to connect the interface with the ESTs.

The motors on the PASS cannot be driven directly by logic. Amplifiers are needed to deliver enough power. These amplifiers are not included on the interface print. In stead an already available driver is used. This saves times for the development and testing of the amplifiers. The steering signals of the amplifiers are TTL compatible. When another type of motor is used, another type of amplifier can be used with the same steer signal.

The following actuators and sensors need to be connected to the ESTs.

- 5 Motors
- 5 Quadrature encoders
- 16 Sheet detectors
- 2 Array sensors

The signals of the actuators and sensors can be found in Appendix IV. The actuators and sensors have a total of 52 signals. The maximum number of signals that can be connected to one EST is 72. It is possible to connect all sensors and actuator to one EST.

#### Scenarios

The tests that are described do not give a good impression on how the actuators and sensors are connected to the ESTs. Therefore several scenarios are introduced which provide a platform on which all test can be performed. Before introducing these scenarios the actuators and sensors are grouped. This is done because several actuators and sensors are related to each other. Each pinch consists of a motor with a quadrature encoder and four surrounding paper detectors. The PIM consist of one pinch (with actuators and sensors) and one extra motor with a quadrature encoder. When the PIM or a pinch is mentioned in this paragraph it is a reference to these groups. The array sensor is not mentioned in the different scenarios. This is because it has no real impact on the scenarios. The array sensor is only used during the calibration phase. Therefore it has no impact on the controller behavior and it can be connected to each EST of the MESS.

List of scenarios:

- Scenario 1: The PIM and pinches are all controlled by one EST.
- Scenario 2: The PIM is controlled by one EST and all other pinches by another EST.
- Scenario 3: The PIM is controlled by one EST and the other pinches by each its own EST.
- Scenario 4: The PIM is controlled by one EST, the following two pinches by one EST and the last pinch by another EST.
- Scenario 5: The PIM and the first pinch are controlled by one EST and the other two pinches by another EST.

- Scenario 6: The PIM (including the actuators and sensors) is controlled by one EST, all motors by another EST, all encoders by another EST and all sheet detectors by another EST.

The first five scenarios only differ in the connection of the pinches on the ESTs. Only the sixth scenario has complete different connections. Figure 14 is a schematic representation of one of the scenarios. This figure shows the connections between the PASS and the ESTs. The figures of the other scenarios can be found in Appendix IV. Next to the scenarios the appendix contains a cross reference table of the tests and scenarios.

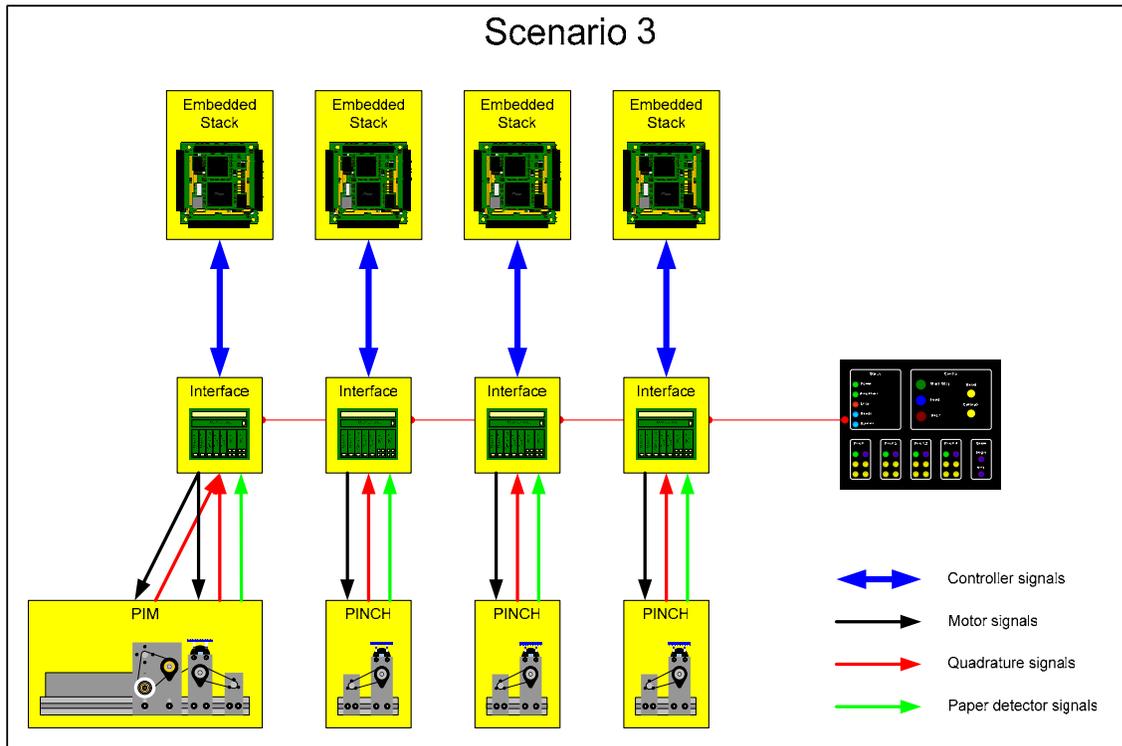


Figure 14 - Example scenario

In the bottom of this picture the mechanical part of the PASS is shown. It is divided in the PIM and the three separate pinches. These actuators and sensors are connected to several small interface prints which in turn are connected to the ESTs via the earlier mentioned flat-cable. On the right of the picture there is a control panel. The control panel will be explained in the next section.

Most scenarios only differ in the connections between the pinches and the ESTs. Therefore the choice was made to make several small identical interface prints instead of one large interface print. These interface prints each have the facilities for one pinch. This way it is easy to change the connections between the pinches and the ESTs and thus switch between scenarios. With this configuration each EST can control up to three pinches. For the PIM there are additional facilities needed which will be addressed later on. This configuration is also not sufficient for scenario 1. In this scenario the PIM and all pinches are connected to one EST. To make this possible the interface prints was extended to have the facilities for two pinches. With this configuration three prints have the facilities for six pinches. One of these pinch connections can be used for the extra motor and quadrature encoder of the PIM. Only scenario 6 is not possible with this configuration. For scenarios 6 the limitation is not the number of pinches connected to one EST but the number of actuators and sensors connected to one interface print. To solve this problem all interface prints have the facilities for 3 pinches without extra sheet detector sensors. Furthermore one extra interface print is needed for the paper detectors. This makes scenario 6 possible. Finally a serial interface for the array sensor is added to the interface print.

## General solution

The interface of the pass consists of several smaller interface prints. These interfaces must contain the facilities for:

- 3 Motors
- 3 Quadrature encoders
- 8 Sheet detectors
- 1 Array sensor

To be able to see the status off the PASS without using the ESTs a control panel is added. The control panel can also be used to send signals to the ESTs. This could for instance be used to start or stop a demonstration. This control panel is an extension to the setup that is not required but is a nice asset to the PASS. Because of the limited time span of this project only the facilities on the interface prints are made and not the control panel itself. The facilities for the control panel are difficult to determine without knowing which signals are needed for the control panel. To leave this choice open all signals will be monitored. Because of the high number of signals duplicating the signals would lead to an enormous increase in wires of which only a few will be used for the control panel. Therefore a microcontroller is added to the interface print which monitors all signals. The microcontrollers on the interface prints are connected to each other and to the control panel via a serial bus.

### 3.2.2 Detailed design

#### Connections

If all facilities mentioned in the previous sections are implemented the number of signals that are needed will exceed the number of signals available in the connection with the EST. This is no problem because not all facilities are needed at the same time. Therefore some signals from the EST can be shared. This leads to two different configurations. Table 3 gives an overview of the connection and shows the two different configurations.

Anything IO Connector							
Configuration 1	M1	M2	SI	Q1	Q2	SD1..4	SD5..8
Configuration 2	M1	M2	M3	-	Q1	Q2	Q3 - SD5..8
* Unused part of connector							

Table 3 - Interface print connections

Explanation of the abbreviations:

- M1..M3 - Motor connectors
- Q1 .. Q3 - Quadrature Encoder connectors
- SD1 .. SD8 - Sheet detector connectors
- SI - Serial interface connector (Array sensor interface)

All the functions that are described in this table will be available on separate connectors. All the connectors from different function will differ to ensure that the right type of sensor or actuator is attached to the connector. As a result of a mix-up the sheet detectors (SD) are called paper detectors (PDs) in the electrical design. In the remainder of this thesis the term sheet detector will still be used. The pinning of the connectors can be found in Appendix V. Connectors that overlap in the different configurations cannot be used at the same time. The EST needs to facilitate in these configurations. This will be addressed in the next chapter.

#### Standard circuits

As mentioned earlier, another function of the interface is the protection of the anything IO board and the sensors. For this reason standard input and standard output circuits are used. The standard input and output circuit both use inverters. This leads to inverted actuator and sensor signals. This should be solved in either the control software or the FPGA.

#### Standard input

If the FPGA on the anything IO board is programmed wrong the possibility exists that a sensor and an IO pin of the anything IO board both drive the same line. If this happens one of the two might break

down. A standard input circuit is added to all the input to prevent this from happening. This standard input circuit is shown in Figure 15.

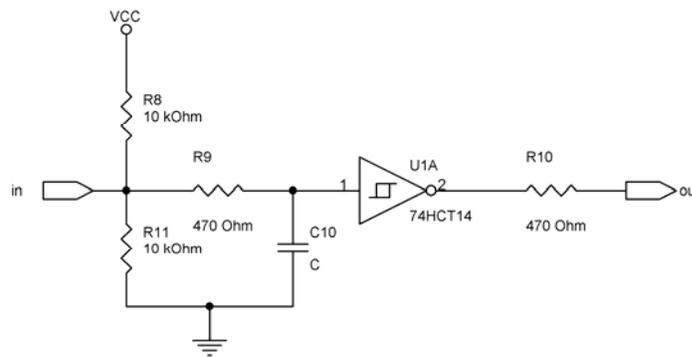


Figure 15 - Standard input circuit

The resistor connected to the output is for the protection of the anything IO board. This resistor limits the maximum current to a maximum of 10,6 mA. Both the inverter and the FPGA can deliver this amount of current. Next to this protection the input circuit has additional features. The sheet detectors and quadrature encoders that are used are open collector sensors. Therefore a pull-up resistor is needed. Also a pull down resistor is present in case that another type of sensor is used. The other resistor and the capacitor can be used as a low pass filter to suppress sensor noise. When a certain feature is not needed the components are left out.

### Standard output

Next to the input the outputs are protected against short circuiting. The FPGA used on the anything IO board has a 3.3 Volt power supply. This means that the FPGA steers the outputs with this low voltages. For the actuators that are used now this is no problem but this might be a problem when other actuators are used. To solve this problem an inverter is added to ensure a good steer signal. The standard output circuit is shown in Figure 16.

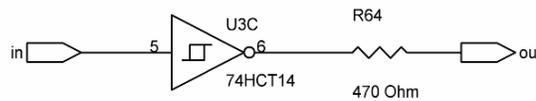


Figure 16 - Standard output circuit

### Control panel interface

As mentioned before the setup will be extended with a control panel. This control panel will show the status of the PASS and can be used to control the demonstrations and experiments with input signals. Output to the controller panel and the input from the controller panel is both low frequent. The human eye can only detected around 50 Hz and input is never higher than a few hertz. Therefore the speed of the microcontroller is not a decisive factor. The microcontroller has to have enough inputs to monitor all signals on one interface print and have serial communication means. With this and the price in mind an Atmel was chosen for this purpose. The chosen Atmel contains analogue inputs and an analogue compare which might be useful for future sensors. The Atmel can then be used to convert the analogue signal to digital signals. Therefore the interface print is extended to facilitate these analogue features.

#### 3.2.3 Implementation

The design of the schematic was done with the program Orcad 10.3. Choices for components were made mainly on availability. The layout of the print was made with the program Orcad 10.3. The size of the print is determined by the size and the number of connectors. These are place on the edges of the print. The remainder of the components could be placed within the region of these connectors. The schematics and the print layout can be found in Appendix V.

### 3.3 Integrated PASS

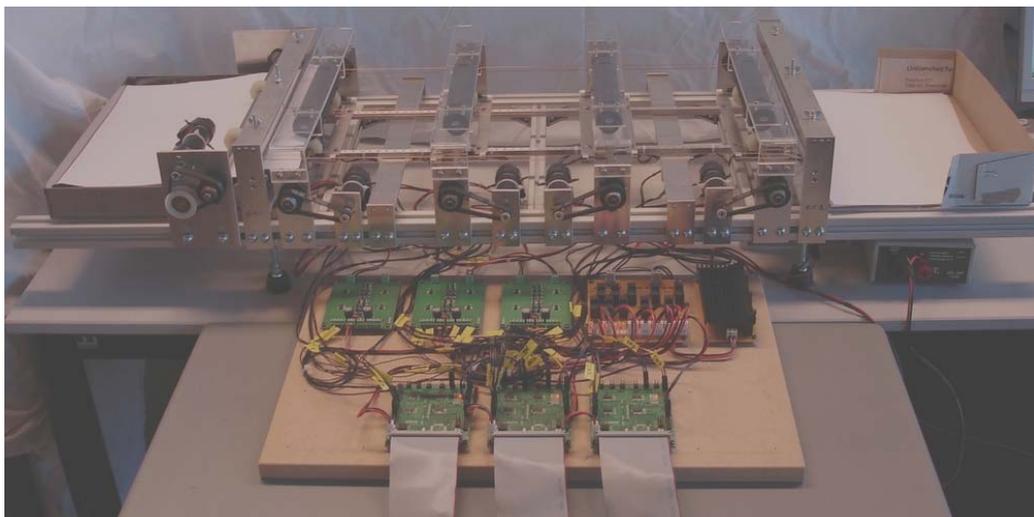


Figure 17 - Picture of the PASS

Figure 17 shows the developed PASS. All components described in this chapter are visible. From left to right the following components can be made out. On the top left the PIM followed by its pinch. The PIM is followed by three more pinches and at they end the paper en tray. Between the pinches the guides and sheet detector can be seen. In front of the mechanical construction the bottom plate with the electrical part can be seen. On the back side the motor amplifiers and the power distributions and in front the interface prints.

Although the PASS is operational it is not completely finished. The bottom plate on which the electronics are placed will be replaced and placed underneath the PASS. Eight sheet detectors are not yet connected to the interface prints. The cables for these sheet detectors and the other components need to be hidden. Three of the five interface prints are finished. This makes most experiments possible.



## 4 MESS integration

This chapter describes the alterations that were made to the ESTs. The alterations were necessary to make the connection between the PASS and the ESTs of the embedded controller. The first section gives an overview of the software structure of the MESS. The second section describes the FPGA design of the Anything IO board. The last section will give an overview of the file system of the EST.

### 4.1 Architecture

The architecture of the MESS is shown in Figure 7 of section 2.1. The software architecture of the MESS is shown in Figure 18.

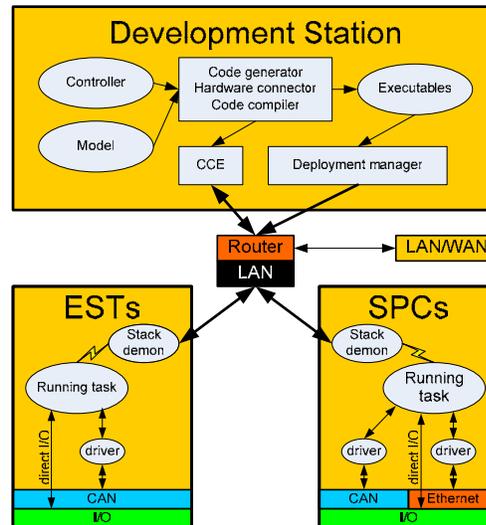


Figure 18 - MESS Software architecture

In this figure the embedded control system of the MESS is represented by the block ESTs. The real embedded control system consists of four ESTs. The virtual engine of the MESS is represented by the block SPCs. The real virtual engine consists of two SPCs. The change of this structure is the router. The router adds extra features. The router assigns the IP addresses to the ESTs and SPCs. The Development station is connected directly to the router or when the development station is placed in a different location a LAN or WAN can provide the connection to the ESTs and SPCs. This gives the possibility of multiple development stations on different locations.

On the development station the Real Time Toolbox of 20-Sim is used to generate code for a controller and, if the virtual engine is used, a model of the PASS. An executable of the model and controller is generated and uploaded to the ESTs and SPCs by the Deployment manager. On the ESTs and SPCs a Stack demon is running which receives the executable and starts the task. The CCE can control the running task with the help of the Stack demon. The I/O is provided by the Anything IO card. This card can be addressed directly by the running task. For communication via CAN or Ethernet a driver is needed. Next to these features the ESTs have a small LCD display (3 lines). This can be used to display short messages on the current status of the EST. This display can be addressed directly.

### 4.2 FPGA Design

Figure 19 is a schematic representation of the Anything IO board.

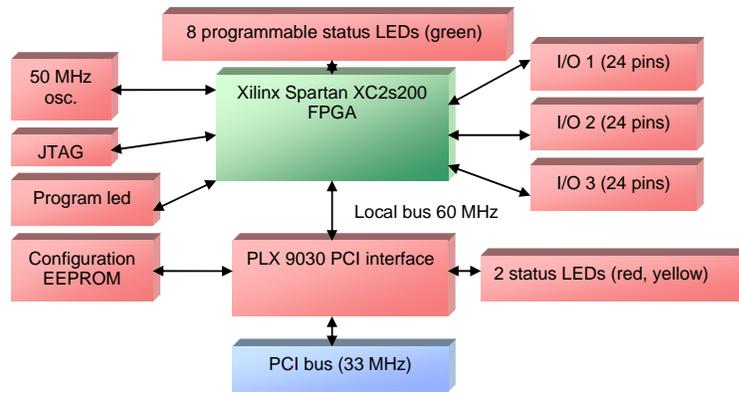


Figure 19 - Anything I/O board layout (Groothuis, 2005)

The heart of the Anything I/O board is a Xilinx Spartan 2 FPGA. This FPGA can be programmed to provide the connections between the surrounding components. The FPGA can be addressed by a PCI bus.

#### 4.2.1 Global design

This section describes the FPGA architecture of the Anything IO Board. The manufacturer of the Anything IO Board supplied several configurations for the FPGA. These include motor control, quadrature encoder support and digital I/O. These configurations were altered and used for the preceding projects. The new and initial configurations do not have a good structure and are difficult to change and maintain. Figure 20 show a schematic representation of the new architecture.

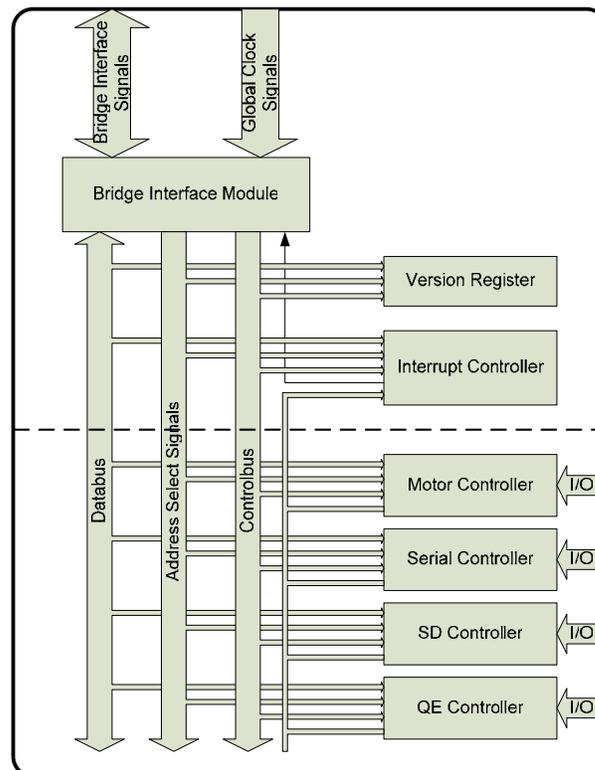


Figure 20 - FPGA Architecture

This FPGA architecture is a module based architecture. All blocks represent a module with each its own functionality. Although this architecture is designed for the MESS it also can be used in other projects. Because of the module based structure it is easy to add and remove modules.

The outer line of this figure represents the boundaries of the FPGA. The Bridge Interface Module (BIM) takes care of the communication with the PCI interface of the Anything IO Board. Each module has the same type of interface. This interface contains signals from and to the BIM and module specific I/O signals. Above the dotted line are two modules which are present in most configurations. The next sections describe all modules in more detail.

All details about the configurations, the modules and the memory map can be found in Appendix VI

### 4.2.2 Design details

#### MESS

MESS is the top level of the architecture. In this design file all connections between the modules and to the outside are made. Furthermore the memory addresses for the modules are defined.

In section 3.2.2 two different configurations are mentioned. For each of these configurations a separate FPGA design is created. The modules bases design makes it easy to implement this. The FPGA designs only differ in the modules and the number of sensors and actuators that the modules support.

As mentioned in the previous chapter the input and output signals are inverted. All in- and output signals are converted on the top level. The signals of the quadrature encoder sensors are open collector. When detection takes place they create a low signal. The same can be said from the sheet detectors. These signals are inverted by the interface and represent the correct value when entering the FPGA. All output signals need to be inverted.

#### Bridge Interface Module

The bridge interface module takes care of all communications to the PLX-Chip. This chip is situated on the Anything IO Card and takes care of the communication to the PCI bus. The BIM controls the data bus and other connections to the PLX interface. The address bus is decoded and combined with the read and write signals of the PLX. This generates read and write select signals for the modules. All addresses are decoded for a 32 bit data bus width. The PLX interface limits the maximum number of addresses to 64 in the 32 bit mode. The BIM has no internal registers.

#### Version Register

The version register contain fixed values which indicate the version of the configuration. This information can be used by the controller to validate the correct configuration. These values can be set during the inclusion of this module in the MESS top design. The version register consist of four eight bit values which are placed on the 32 bit bus. These values indicate the project, the design, the version and subversion.

#### Interrupt Controller

When needed the interrupt controller can be added to handle all interrupt from the other modules. The number of interrupt can be configured during the inclusion of the module. The number can not exceed the data bus width. The interrupt controller consists of a mask register, an interrupt register and a missed register. The mask register indicate which interrupt are activated. The interrupt register indicate which interrupt was activated. The interrupts can be clear per bit. The missed register indicates when a second interrupt occurred before the interrupt register was cleared.

#### Motor Controller

The motor controller was extracted from the preceding projects. This was done to reduce development time and use a tested version. The motor controller (PWM controller in previous projects) was entwined with the quadrature encoder controller. In the new motor controller there is no relation with the quadrature encoder controller. The motor controller has a global register to enable/disable all motors at the same time. The number of motors can be configured during the inclusion of the module. Next to this each motor has its own control and value register. The value register contains a two's complement value which determines a PWM signal and a direction signal. An enable signal can be activated by the control register.

### **Serial Controller**

Because of the limited time span the serial controller is not implemented yet.

### **SD Controller**

The sheet detector (SD) controller read the status from the sheet detectors. This can be seen as digital input. The number of sheet detectors can be configured during the inclusion of the module. The sheet detectors are read as one 32 bit value therefore the number of sheet detectors cannot exceed 32.

In the electrical the sheet detectors were called PDs. To limit the confusion this is also the case in the FPGA configurations.

### **QE Controller**

The quadrature encoder (QE) controller was extracted from the preceding project. This was done to reduce development time and use a tested version. As stated before this quadrature encoder controller and the motor controller were entwined. The new quadrature encoder controller has a global register to enable/disable the counters and to clear the counters. The number of quadrature encoder input can be configured during the inclusion of the module. All quadrature encoder have a control register and a counter value register.

#### **4.2.3 Implementation**

The implementation of the FPGA configuration was done in VHDL. The Xilinx Integrated Software Environment (Xilinx, 2004) was used as development environment. This tool checks the VHDL code and creates a bit file which can be used to program the FPGA of the Anything IO board. During the implementation problems with timing occurred. This was also the case with earlier developed configurations. Although testing indicates no problems as a result of these timing errors they could surface in the future. The problems surface after including the Motor and QE Controller. These modules should be investigated to solve this problem.

#### **4.2.4 MSCT integration**

To be able to communicate from 20-Sim to the two new FPGA configurations the MSc tool needs to be configured. For each FPGA configuration a new target is added. This target is defined in an XML file. This file contains all details for the configuration. These details are:

- Number and type of in and output
- Initialization functions for each in and output
- Read and write details for each in and output

In the original file it is not possible to define other initialization, read and write functions for different type of in and output. Therefore the initialization, read and write functions are extracted from the XML file. The functions are written in a C-file. The XML file was adapted to include this C-file and call the right functions

Most functions are straight forward. Two functions are explained in more detail.

#### **Version register**

The version register of the MESS is used during the initialization phase. The version number of the FPGA configuration is written on the screen before the simulation starts.

#### **Quadrature encoder**

For the quadrature encoders an extra functionality is added. The quadrature encoders count the pulses which represent a displacement. Sometimes it is wanted to have velocity readout. For this reason an extra function has added. In the XML file an extra input is defined. The velocity input exists next to the normal quadrature encoder inputs. The velocity is deducted by storing the previous number of pulses and subtracting the new value. After this the step-size of the control loop is used to convert it to pulses per second.

### 4.2.5 Result

The integration of the MSCT was the final Phase in completing the test environment. It is now possible to create controllers in 20-Sim, connect the models to hardware with the MSCT and log all data with the logger from the CCE tool. Figure 21 shows a picture of the mess.

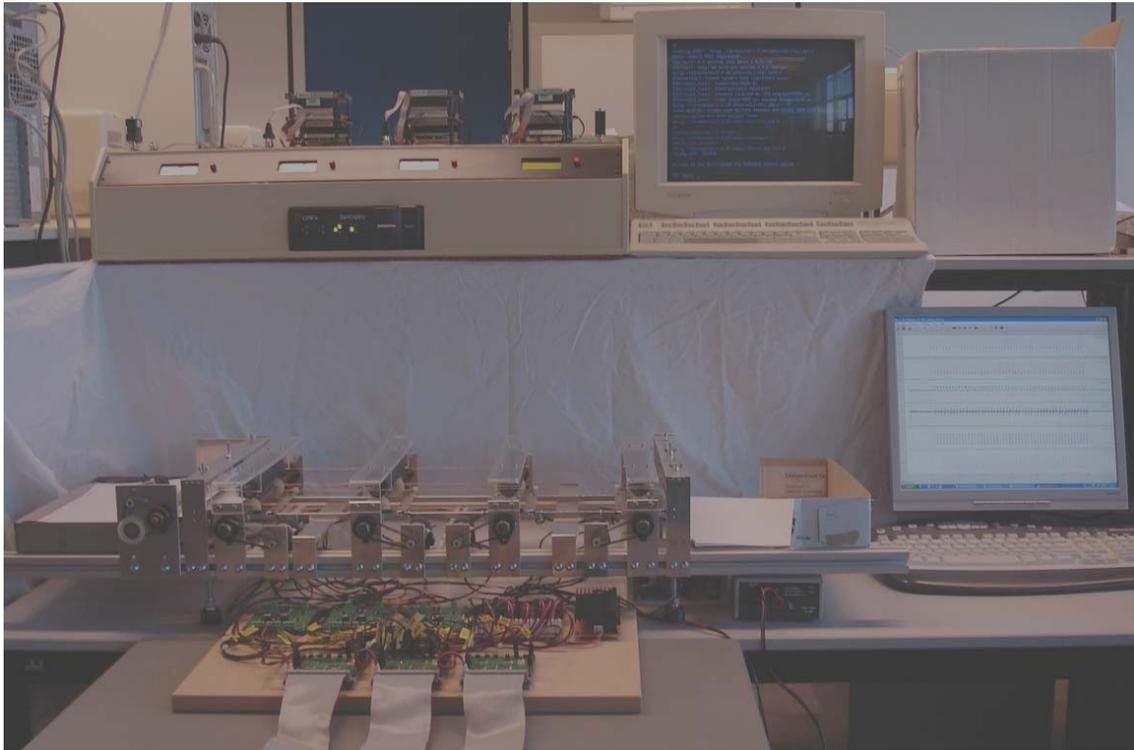


Figure 21 - Picture of the MESS

The PASS is placed in the front of the picture. In the top of the picture the embedded control system with three of the four EST can be seen. The monitor on the bottom right is from the development station. The simulation PCs of the virtual engine are not represented in this picture.



## 5 Experiments and results

In contrary to the application experiments described in section 2.2.2 the experiments in this describes were performed only for validation of the MESS. The application experiments will be performed in the Boderc project.

The experiments that were performed include a calibration method and measurements on the precision of the MESS. All experiment details and experiment results can be found in Appendix VII.

### 5.1 Experiments environment

The experiment environment uses the software architecture described in section 4.1. In the experiments the PASS will be connected to the ESTs of the embedded control system. Figure 22 shows the top level controller architecture. To be able to simulate in 20-Sim all inputs need to be defined. Figure 22 shows the top level controller architecture. All input and outputs are defined in this top level controller.

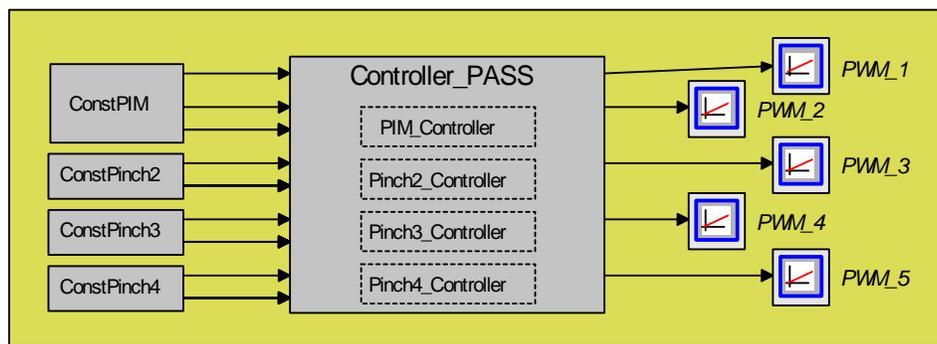


Figure 22 – Top level controller architecture

On the left side of the figure there are four sub-models which give a constant set-point to all controllers. The Controller\_PASS is the model that contains the top level controller. The signal monitors on the right are connected to the PWM outputs. Inside the Controller\_PASS model there are four sub-models. Each sub-model handles the input and output of a part of the PASS. In future experiments this hierarchy can be used for controller design of the PASS.

The MSCT allows only code generation from sub-models. This ensures that input and output are defined and code can be generated for the controller and the plant separately. In case of a single controller code is generated for the Controller\_PASS sub-model. In case of a distributed controller code is generated for each sub-model inside the Controller\_PASS. The MSCT is used to create an executables and upload the executable to the ESTs.

The input and output signals of all experiments are logged. The logging of the signals is performed with the logger tool of the Command and Control Environment which is described in section 1.2.2. The results are imported in the simulator of 20-Sim. The plots of the results can be found in Appendix VII.

### 5.2 Unit experiments

This section describes the experiments which are performed to validate the correct working of individual components. The sheet detectors are an example of such a component.

These experiments are performed before calibrating. Measured values are used as a base for all parameters. Errors in these measurements result in slightly different results. More details on errors can be found in the calibration section of the chapter.

#### 5.2.1 Interfaces

The correct working of the interface prints will be validated by testing the actuators and sensors. During the following experiments all actuators and sensors are used. The correct working of the interface prints is validated if no problems surface during these experiments.

### 5.2.2 Actuators and sensors

The actuators and sensors are tested with the same controller. No paper is inserted in these experiments. Details on the experiments and plots of the results can be found in Appendix VII.

### Motors and Quadrature encoders

The quadrature encoder is fixed to the motor. The validation of the motors and quadrature encoders are performed in the same experiment. The amplifiers of the motors are steered with a fixed PWM value. The expected result is a relative constant motor velocity. The velocity input of the quadrature encoders is used to validate the correct working of the motor and quadrature encoders.

All motors and quadrature encoders are working as expected.

### Sheet detectors

The validation of the sheet detectors is performed with the experiment described in the previous section. For a fraction of a second a paper sheet is placed above each detector to test the correct working. The expected result is a pulse each time a paper sheet is above a sheet detector.

The test results indicate that not all sheet detector work as predicted. A number of sensors placed underneath the top roller are not working well. The top roller reflexes a part of the light beam. As a result the sheet detectors react slow or do not work at all. There are three possible ways to solve this problem. These solutions are:

- Move the sensor to prevent reflection of the light.
- Place a light absorbing material above the sensor.
- Place a light reflecting material above the sensor to redirect the light beam away from the sheet detector.

Moving the sensor is an unwanted solution. The sensor is placed further away from the pinch. Placing light absorbing material is a good solution if the right type of material is used. Short test indicated that placing a reflecting material is a good and simple solution.

The accuracy and speed of the sheet detectors is measured in section 5.4.

### 5.2.3 PIM

This section describes the experiments that validate the performance of the PIM. The PIM determines the input speed and inter sheet distance of the paper sheets. The PIM should feed only one paper at the time. Several experiments were performed to validate these aspects.

The experiments on the PIM are performed with the single controller which is described in section 5.3. This section also describe the calculations which are needed to control the inter sheet distance and the speed of the PASS.

The single controller uses a proportional controller with a set-point generator to control the velocity of each pinch. The PIM has a proportional controller with a pulse generator. The pulse generator generates a pulse for each paper sheet. The frequency of the pulses determines the sheet interval. The interval of the paper sheet and the velocity of the pinches can be used to control the inter sheet distance.

Details on the experiments and plots of the results can be found in the Appendix VII.

### Multiple sheets

Initial experiment indicated that there are several aspects that influence the performance of the PIM. These aspects are:

- Rubber layer of the PIM (described in section 3.1.2)
- Speed of the paper

- Quality of the paper

Additional experiments were performed to test the influence of these aspects. All experiments are set to produce 50 paper sheets with an inter sheet distance of 50 mm. Five experiments will be compared. These experiments are:

- New paper without rubber layer, 100 PPM
- New paper, 50 PPM
- New paper, 100 PPM
- Used paper, 50 PPM
- Used paper, 100 PPM

The experiments were performed by counting the sheet after each experiment. Every experiment is only performed ones.

Table 4 shows the results of these experiments.

Experiment	Sheet Count	Double sheets
Without rubber	59	9
Used, 50 PPM	54	4
Used, 100 PPM	55	5
New, 50 PPM	53	3
New, 100 PPM	52	2

50 mm inter sheet distance

Table 4 - Double sheet count

The results show a significant improvement when a rubber layer is added. The difference of new and used sheets are present but smaller. Double sheets still occur. Possible solutions to these problems are:

- Using another type of rubber layer. Test of different types if rubber can be found in (Suzuki et al., 1998).
- Changing the pickup method. First push a paper sheet backwards to free the paper then feed the paper sheet to the paperpath.
- Look for a better design for the PIM. Different solutions can be found in (Suzuki et al., 1998).

During the test some additional visual observations were made. Visual observation of the experiment without the rubber layer indicated a number of faults. During this experiment a number of paper sheets entered the paperpath under a large angle (estimated to more than 5 degrees). The cause of this problem is the manner in which the PIM grasp the paper. The roller of the PIM has two contact points on the paper sheet. This can be seen in **Error! Reference source not found.** When the roller is roller is accelerated slip occurs. A paper sheets enters the paperpath with an angle if on of the two contact points grasp the paper sheet before the other contact point. Similar problems were not observed during the other experiments. The friction of the rubber layer holds back the paper sheets until both contact points grasp the paper sheet.

A second observation was made. In the experiment without the rubber layer the PIM fed the paperpath up to four paper sheets at the same time. This was not observed during the other experiments. During the other experiments the double sheets were shifted less then 1 mm. Because of this double sheets might not cause a problem in future experiments.

#### Inter sheet distance of paper

The PIM determines the inter sheet distance of the paper sheets. The first motor of the PIM feeds paper sheets into the paperpath with a fixed interval. The paper sheets in the paper tray of the PIM are not completely aligned and often there is a delay before the rollers grasp a paper sheet. This leads to deviations in the inter sheet distance of the paper. The experiments described in this section measures the deviation caused by the misalignment and the slip of the first roller.

In all experiments the PIM is set to feed 50 paper sheets. The controllers of the PIM and pinches are set to a specific velocity to control the inter sheet distance and speed of the paper sheets. Eight different experiments are performed. These setting of the experiments are:

- New, 10 mm inter sheet distance, 50 PPM

- New, 10 mm inter sheet distance, 100 PPM
- New, 30 mm inter sheet distance, 50 PPM
- New, 30 mm inter sheet distance, 100 PPM
- New, 50 mm inter sheet distance, 50 PPM
- New, 50 mm inter sheet distance, 100 PPM

The deviation of the inter sheet distance was determined by calculating the front edges of the paper sheets when they enter the first pinch. The velocity of the first pinch is set higher than the velocity of the PIM roller. The PWM signal of the first pinch increases when a paper sheet enters the first pinch. The difference in quadrature pulses of two such events are used to determine the distance between the front edges of two succeeding sheets.

The sheet detectors can also be used to determine the deviation of the PIM. In the experiments in this section the sheet detectors were not calibrated. When the sensors are calibrated they could be used to repeat the experiment and compare the results.

Table 5 shows the results of the experiments. All experiments were performed one time.

Experiment	Maximum deviation	Standard deviation
New, 10 mm, 50 PPM	1,527	0,618
New, 10 mm, 100 PPM	2,913	0,938
New, 30 mm, 50 PPM	1,735	0,660
New, 30 mm, 100 PPM	3,576	1,434
New, 50 mm, 50 PPM	1,407	0,661
New, 50 mm, 100 PPM	3,213	0,678
Used, 50 mm, 50 PPM	1,695	0,864
Used, 50 mm, 100 PPM	3,734	1,343

Table 5 - Deviation of the inter sheet distance

At higher speed the deviation is larger. These results indicate that the PIM is more reliable at lower speeds than at higher speed. The influence of the inter sheet distance does not show a real clear relation. The experiments need to be repeated to get more accurate results.

The difference as a result of the speed could also be a result of measurement error. Details on measurement errors can be found in section 5.4.

### 5.3 Integrated experiments

The experiments described in this section are used to validate the complete MESS. There are two experiments that will be performed. The first experiment uses a controller on a single EST. The second experiment the controller is divided on three ESTs. Both experiments use the same type of controller and will operate at 100 PPM. The results of both experiments are compared.

These experiments are performed before calibrating. Measured values are used as a base for all parameters. Errors in these measurements result in slightly different results. More details on errors can be found in the calibration section of the chapter.

#### 5.3.1 Controller design

There is a separate controller for each motor. All these controllers are the same. The controllers are proportional controllers with velocity feedback. The value of the proportional controller is determined with the Ziegler-Nicholas method. This method determines the proportional value with a rule of thumb. The proportional value is increased until the system starts oscillating. The proportional value and oscillating frequency is used to determine the parameters for a P, PI or PID controller. In this case only a parameter for the proportional controller is used. Details on the calculations and the values can be found in Appendix VII.

During the first experiments problems with the velocity input of the quadrature encoders surfaced. If the PASS operates at 20 PPM with a inter sheet distance of 50 mm the quadrature encoder of the pinches generate pulses at 4 kHz. A control loop that operates at 1 kHz receives 4 pulses each loop. The precision is too low when this value is used to calculate the velocity. There are two easy ways to

solve this problem. Past values can be used to calculate an average of, for instance, the last 20 values. Another solution is a slower control loop. This is used in the experiments of the MESS. The calculations on of the pulse frequencies can be found in the next section.

Both experiments use a control loop of 100 Hz. Figure 23 shows the controller which is used in the experiments.

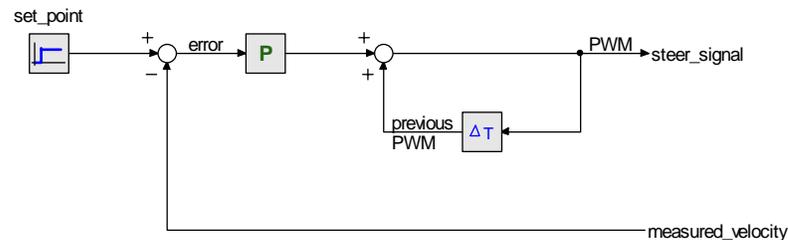


Figure 23 - P-Controller

The set-point determines the desired velocity at a certain moment (depending on the experiment). The PIM controller uses a pulse generator to feed one sheet at the time. The measured levocity on the left is connected to the velocity input of the quadrature encoder. The error of the desired velocity and the measured velocity is amplified and added to the previous PWM value. The output is connected to the PWM output which drives the motor.

### 5.3.2 Parameter calculations

All parameters in 20-Sim are calculated in an MS Excel sheet.

Settings and fixed values		
Parameter	Value	Unit
Paper print length	210	mm
Inter sheet distance	50,0	mm
Pages per minute	100	ppm
Roller diameter	27,8	mm
Belt Gearing	2,056	
Extra Gearing	4,800	
Quadrature pulse count (pulses/rotation)	2000	

Calculations		
Parameter	Value	Unit
Paper velocity	0,433	m/s
Roller circumference	87,3	mm
Roller speed	4,962	rps
PIM motor velocity	48,955	rps
Pinch motor velocity	10,199	rps
PIM pulse gen omega	10,472	rad/s
PIM Quadrature pulse frequency	97,910	kHz
Pinch Quadrature pulse frequency	20,398	kHz
PIM displacement per pulse	4,425825	$\mu\text{m}$
Pinch displacement per pulse	21,24396	$\mu\text{m}$

Table 6 - Parameters calculations

The roller diameter is a measured value with a limited precision. The displacement per pulse is calculated from this value. As a results the displacement per pulse may deviated from the reality. More details on precision can be found in section 5.4.

### 5.3.3 Single controller

The single controller uses the connections which are described by Scenario 1. Details on this scenario can be found in Appendix IV. The controller is uploaded to one EST and all input and output signals are logged. The results are imported in 20-Sim.

Figure 24 shows the results of the experiment with the single controller.

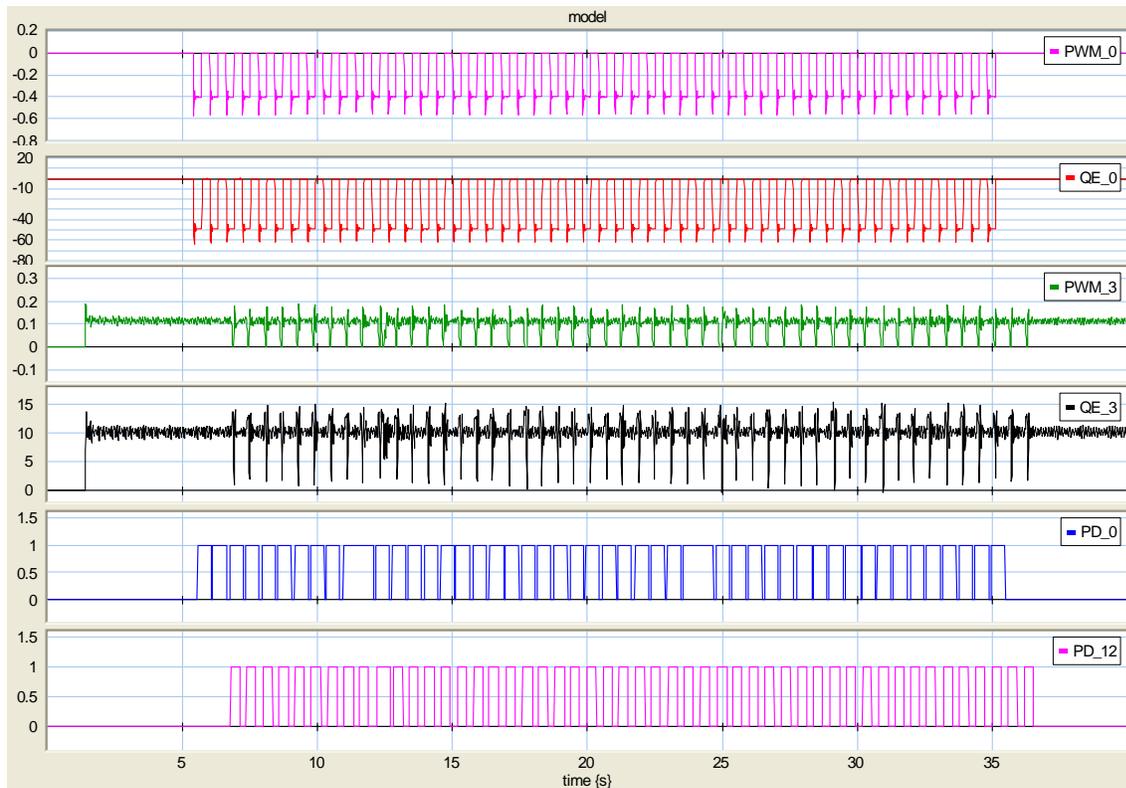


Figure 24 - Experiment result of single controller

In the figure several aspects can be seen. The PWM and quadrature encoder of the PIM are inverted. The roller is mounted on top of the paper instead of the bottom therefore the roller has to rotate in the opposite direction. The PWM\_0 contains exactly 50 pulses in 30 seconds. This was expected because the speed of the PIM was set to 100 PPM. The first sheet detector (PD\_0) is placed close to the PIM. Inter sheet distance was set to 50 mm. This is not always measured. This is a result of the deviation of the PIM and the slow response of the Sheet detector. More details on the precision of the sheet detectors can be found in the next section. The spikes of which can be seen in the PWM\_3 and QE\_3 are the result of the velocity difference of two pinches. When a sheet is present in two pinches both motor try to keep their velocity. As a result spikes appear. The spacing between the pulses of the last sheet detector (PD\_12) is larger. The velocity of the last pinch is much higher. As a result the spacing between the paper sheets is much larger. The speed of the last pinch is increased to ensure a good stacking of the paper sheets in the paper tray.

## 5.4 Calibration

This section describes the calibration of the PASS. The calibration has to function. The calibration is used to determine the position of the pinches and sheet detectors. The second function is to determine the accuracy and speed of the sheet detectors. This section starts with an introduction which is followed by remarks on the measurement errors.

### 5.4.1 Introduction

Calibration is needed to increase the precision of measurement on the setup. The roller diameter, position of the pinches and position of the quadrature encoders are all measured. This measurement is performed with limited precision. For instance, the position of the pinches is measured with a precision of millimeters. The calibration method described in this section contains three steps.

The steps are:

- Determine the roller circumference.
- Calibration of the pinches.
- Calibration of the sheet detectors.

Before introducing these calibration methods a section on measurement errors is presented.

### 5.4.2 Measurement errors

In the experiment measurement error occur as a result of the limited precision of sensors. In the calibration method the quadrature encoders are used to for the calibration method. There are two types of errors that occur by measuring. These errors are related to the velocity and position.

Calculations made for the speed are described in the section 5.3.2.

#### Velocity

The experiment described in this chapter all use velocity control. A disadvantage of the velocity control is the short interval in which the pulses has to be measured. Low quadrature frequencies lead to small values between to pulses. Table 7 gives an overview of the pulse count for velocity readout.

Settings	Pulse count	
	PIM	Pinches
20 PPM, 100 Hz	195,8	40,8
20 PPM, 1 kHz	19,6	4,1
100 PPM, 100 Hz	979,1	204,0
100 PPM, 1 kHz	97,9	20,4
50 mm inter sheet distance		

Table 7 - Pulse count for velocity readout

The table show for different speeds of the setup and the measurement frequency (control loop frequency). The pulse count of the PIM and the pinches differ because of the extra gearing of the PIM motor. Because of the small pulse count at lower speed the experiment in this chapter all operate at 100 Hz. This gives a minimal pulse count of 40,8 pulses.

#### Position

For calibration a precise position measurement is needed. The precision of the measurement are related to the precision of the sensor, the speed of the experiment and the measurement frequency (control loop frequency). Table 8 gives an overview of the error at different speeds and frequencies.

Settings	Error	
	Pulse count Pulses	Distance mm
20 PPM, 100 Hz	40,8	0,867
20 PPM, 1 kHz	4,1	0,087
100 PPM, 100 Hz	204,0	4,333
100 PPM, 1 kHz	20,4	0,433
50 mm inter sheet distance, 21,2 $\mu$ m per pulse		

Table 8 - Position error

The error distance is determined by the pulse count and the roller circumference. A higher measurement frequency results in a smaller error. A lower calibration speed also reduces the error.

During the calibration method described in the section a 100 Hz control loop frequency was used. The calibrations should be repeated with a high control loop frequency to reduce the error.

### 5.4.3 Roller circumference

The roller circumference is used in the calibration method. The circumference was measured with a low precision. This section describes a method which uses the known distance of a paper sheet to calculate the roller circumference. It is important that the length of the paper sheet is precisely known. This can be done by measurements or by using a calibration sheet. The method used uses experiment results of the calibration method of the pinches. Figure 25 show a zoomed part of the experiment result. The paper is inside the middle pinch from the moment it touches the bottom line until the moment it releases the top line. At these moments the difference of the quadrature encoder pulses of

the middle line is calculated. The length of the sheet is divided by the number of pulses. This gives an displacement per pulse. The result of the experiments can be found in Table 9.

Characteristic	Expected	Measured
Pulse count	9885	9893
Paper width (mm)	210,000	
Displacement per pulse ( $\mu\text{m}$ )	21,244	21,227
Pulses per roller rotation	4111	
Roller circumference (mm)	87,336	87,267
Roller diameter (mm)	27,800	27,778
Roller divation (mm)		0,022
Measurement error at 100 Hz (pulses)	40,8	
Maximum measurement error (%)		0,825

20 PPM, 50 mm inter sheet distance, 100 Hz

Table 9 - Roller circumference

The error in the measurement is included in the table. The precision can be increased. Detail on this can be found in section 5.4.2. During the remainder of the calibration method the expected circumference is used. The calculations in this section were performed after they other experiments.

#### 5.4.4 Calibration of the pinches

This section describes the calibration method which is used to determine the position of the pinches. The calibration method uses the single controller described in section 5.3. The PIM operates at the velocity of 20 PPM but only one sheet is fed into the paperpath. The velocity of each pinch increases with  $\pm 10\%$ . All values are logged and imported in 20-Sim.

All positions are determined relative to the first pinch. This means that the PIM and the first sheet detector have a negative value.

Figure 25 show the results of the calibration experiment. The figure is zoomed to the relevant part of the plot. The figure shows the velocity of three succeeding quadrature encoders.

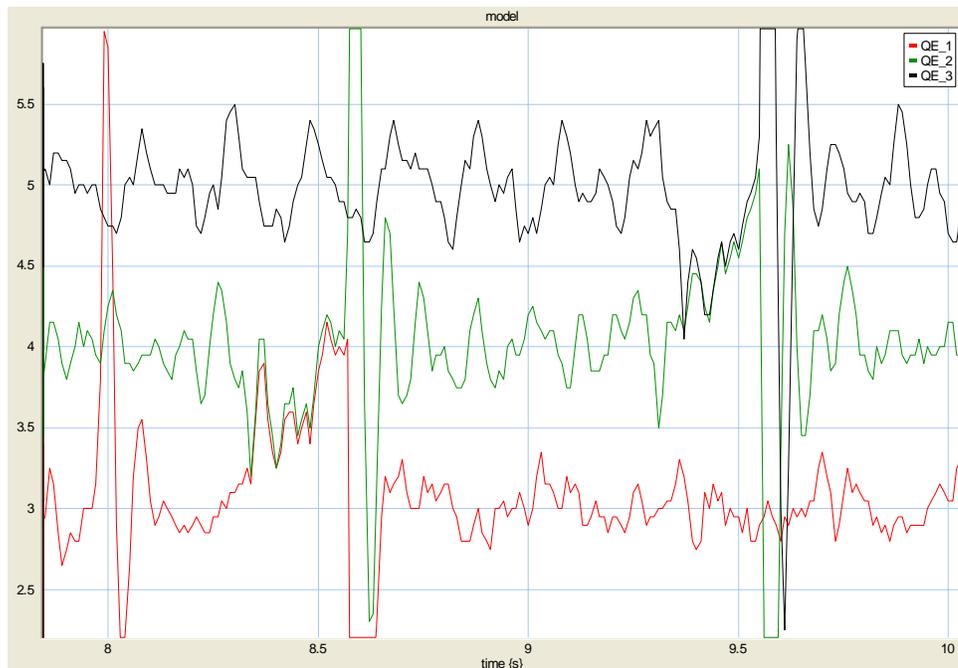


Figure 25 - Calibration of pinch position

The measured velocities of two succeeding quadrature encoders are compared. The distance of the pinches is determined by searching for the moment were a paper sheets enters the second pinch. At this moment the two velocities will approach each other. The distance between the sheets can be deducted from the pulse count of the quadrature encoders. In this figure the distance between the pinch

of the top and the middle encoder can be deducted. This distance is related to the difference of the pulses of the quadrature encoder in the middle.

	Absolute position	Relative Position
	mm	mm
PIM Motor	-81,316	-81,316
Pinch 1	0,000	0,000
Pinch 2	174,838	174,838
Pinch 3	177,281	352,119
Pinch 4	176,367	353,648
Position relative to pinch 1		

Table 10 - Result of the pinch calibration

Table 10 shows the result of the pinch calibration. The precision can be increased. Detail on this can be found in section 5.4.2.

### 5.4.5 Calibration of the sheet detectors

There are two aspects of the sheet detectors that need to be calibrated. These are the accuracy and the position of the sheet detectors.

#### Accuracy

A sheet detector emits a light beam and detects the reflection of this light beam. The light beam has a certain width. As a result there is a small difference in the detection of the front side and the back side of a paper sheet. This section describes the calibration method to determine this difference.

A sheet detector generates a pulse when a paper sheet covers the sheet detector. The width of this pulse is related to the length of a paper sheet. To be able to calibrate the sheet detectors accurately the exact length of the paper sheet should be known. This could be done by measurements or by using a calibration sheet.

The measure width of the pulse can be calculated with the quadrature encoders of the pinches. The pulse difference of the rising edge and falling edge determine the width of measure width of the paper sheets. To be able to count the pulse difference the measurements of the quadrature encoders of two pinches are needed. First the pulses of the first pinch are counted. When a paper sheet enters the second pinch the roller rotate at the same velocity. At this moment the pulses of the second pinch are counted. The total number of pulses determines the width of the paper sheet. The difference of the width of the paper sheet and the measure width determine the accuracy of the sensor.

The accuracy of the sheet detector is determined by the reaction time. The sheet detectors generate a pulse when a paper sheet covers the sheet detector. The width of the pulse is determined by the length of the paper sheet. The reaction time of the sheet detector is determined for both flanks of the pulse.

The results of the experiments for the accuracy of the sheet detector calibrations are not included in the report. The experiment has to be repeated at a higher measurement frequency to increase the accuracy.

#### Position

This section describes the method to determine the position of the sheet detectors. The position of the pinches can be deducted from the results of 20-Sim. Figure 26 assist in the understanding of this method.

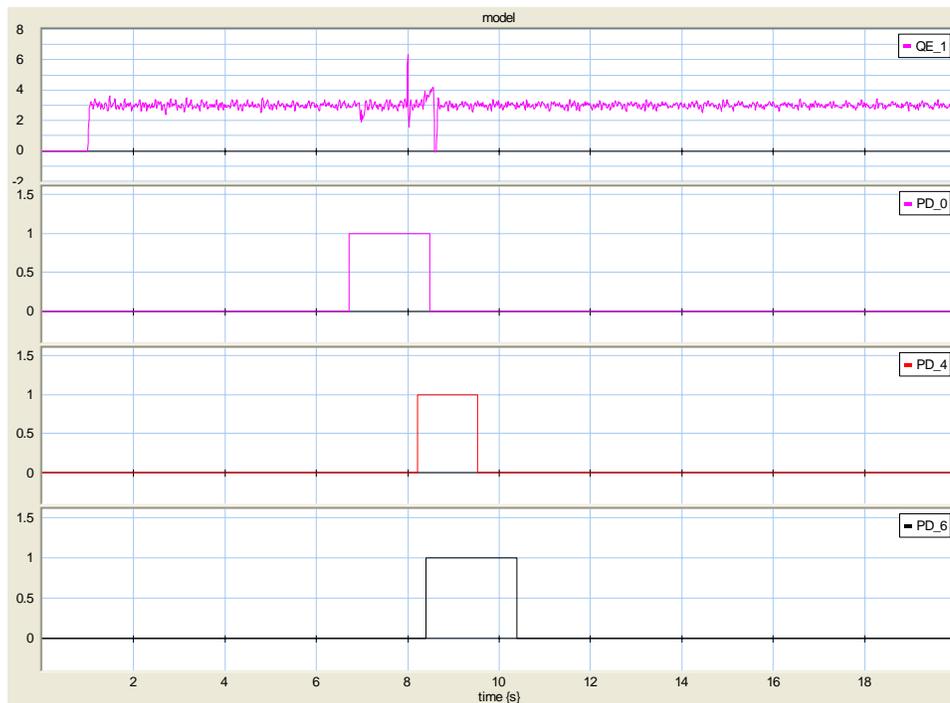


Figure 26 - Calibration of sheet detectors

When a paper sheet passes a sheet detector a high pulse is generated. The front side of the pulse determines the position of the sheet detector. The position readout of the quadrature encoder determines the absolute position. The position is deduced by determining the moment a paper sheet enters the pinch and the moment the paper detector reacts (high pulse). The moment when a paper sheet enters a pinch can be seen as a sudden change in the velocity of the pinch. This is due to the velocity difference of the pinches.

The results of the experiments for the position of the sheet detector calibrations are not included in the report. The experiment has to be repeated at a higher measurement frequency to increase the accuracy.

The calibration method described above does not include the skew (angle) of the paper. When the array sensor is placed the skew of the paper can be measured and the position of the sheet detectors can be adjusted to increase the accuracy of the calibration. This adjustment can be made with goniometric functions.

## 5.5 Validation

This section summarizes the results of the experiments of this chapter. The results of the experiments are compared to required characteristics which are described in 2.2.3.

The PIM and the pinches are capable of operating speed up to 100 PPM with an inter sheet distance of 50 mm. The PIM can be used to change the inter sheet distance. There is some deviation in the inter sheet distance. This can be reduced with a more advanced controller which adjusts the speed of the PIM motor and pinch.

The PIM sometimes passes two sheets to the paperpath at the same time. Further investigation is needed to prevent this from happening.

The correct working of the sheet sensors was validated. A number of sensors show “stick” behavior. The solutions to these problems are described in section 5.2.2. Further testing of the sheet sensors need to be performed. Visual observations of the results indicate that the problems that exist can easily be solved.

The correct working of the interfaces is validated by the correct working of the sensors and actuators. All sensors and actuators are working and therefore the interface print is working as predicted.

---

## 6 Conclusions and Recommendations

### 6.1 Conclusions

The MESS is working.

Although not completely finished all designed functions of the MESS are working. The parts that are not finished are described in the following sections. The MESS is a good representation of the paperpath of a copier. Together with a model of the plant it provides a good simulation platform which can be used to verify HIL simulations. The flexible connections make it easy to change the connections of the actuator and sensors to the EST. This way it is easy to test different control architecture, normal as well as distributed.

#### **Mechanical**

The mechanical part of the PASS is almost finished. Only the mount for the array sensors need to be added and the bottom plate need to be mounted to the setup. Both are minor changes.

The mechanical design matches almost all requirements. The number of pinches and sensors are sufficient. The dimensions are within the limits. The results of the experiments showed that the pinches and motors are capable of reaching the requirements. During these test there are no major vibrations in the frame. The PIM and output tray can contain up to 250 sheets and can output this at the required speed and with variable inter sheet distance.

During the experiments a problem with the PIM surfaced. The PIM sometimes insert two paper sheets at the same time. More thorough testing needs to be performed to find the cause of the problems. Two part of the pinch differ from the design. The rubber layer is made of a different kind of rubber and the springs that are used are slightly different then designed. Improving these parts might solve the problem.

The output tray has a disadvantage as well. At low speeds the paper sheets do not reach the tray. The last pinch needs to speedup the paper in order to reach the tray. If the last pinch is needed for control this might be a problem. The PASS could be extended with a pinch to solve this problem.

The sheet detectors are working. Some of the sensors are not working optimal. They detect the roller mount above the sensor as a paper sheet. There are a few easy ways to solve this problem which are described in the recommendations.

#### **Electrical**

The electrical part of the PASS is almost finished. Three of the five interface prints are finished which provide enough possibilities for a number of test. The interface of the array sensor is not tested yet. All sensors and actuators have their own connectors which provide an easy way to change the position of an actuator or a sensor. The interface prints can easily be connected to another EST. The requirements related to the interfacing are all met.

During the experiment one minor problem surfaced. The outputs of the interface print are undefined when the interface print is not connected to the EST. Problems occur when the interface print and the amplifiers are powered on without a connection to the ESTs. The motor could go on and off randomly as a result of the floating inputs. During the test phase a second predicted problem was investigated. The power supply of the motor amplifiers and interface prints are connected. Disturbances generated by the motors appear on the power supply of the interface prints. This might damage the chips on the interface print or even on the ESTs. These spikes of these disturbances reach up to 1 volt on the power supply of the interface print.

#### **FPGA Design**

The FPGA design works as predicted. The module base architecture provides a good structured design which is easy to understand and changes. Components can be added to extend the functionality of the design. The same structure can be used for the simulation PCs of the MESS. Components developed in earlier projects can be adjusted to be used as a module.

## 6.2 Recommendations

### Extension

A good extension of the MESS is the earlier described control panel. During demonstrations the control panel gives a good overview of the status of the MESS. A control panel is useful to control an experiment. Experiments can be stopped, started and restarted without the use of the controller.

The calibration method described in chapter 5 can be integrated in 20-Sim. This is useful when the positions of components are changed on a regular basis.

An accurate model of the PASS should be made. This is needed for the HIL simulations. Results of the calibration can be used for this model.

### Mechanical

The PASS is functional but the last components of the PASS have to be added. There are three components that need to be adjusted are added. These components are:

- A mount for the array sensor have to be constructed.
- The bottom plate need to be replaced with a metal plate and mounted to the PASS
- The output tray needs to be replaced with a metal version.

The PIM is working but small problems exist. Additional experiments could indicate what the problem is. Small adjustments mentioned in the conclusions could fix the problems.

The last pinch has a minimal speed to ensure that the paper sheets reach the output tray. If this pinch is needed for control a pinch could be added to transport the paper sheets to the output tray.

A number of sheet detectors detect the top roller mount as a paper sheet. This problem should be solved. There are three ways to solve this problem. These are:

- Move the sensor to prevent reflection of the light.
- Place a light absorbing material above the sensor.
- Place a light reflecting material above the sensor to redirect the light beam away from the sheet detector.

Initial testing indicates that placing reflecting material above the sensors is the best solution.

### Electrical

The electrical part is not completely finished. The following parts need to be finished:

- Two interface prints need to be finished and tested.
- The wires should be placed out of sight.

It is recommended to replace the power amplifiers or place a galvanic separation between the interface prints and the power amplifiers. Otherwise the amplifiers might damage the interface prints or even the ESTs.

The output circuits of the interface print could be a problem. This can be solved by patching or replacing the interface prints.

### FPGA Design

There is currently no support for the array sensor in the FPGA design. A serial interface needs to be added to support this feature. The serial interface can also be used for the communication between the Atmel of the control interface and the ESTs.

The components for the motor and quadrature encoders are partly copied from an earlier project. These components contain feature which will never be used. These features can be removed to free space of the FPGA. This could be needed when a serial interface is added.

### Experiments

The experiments described in this thesis are only to validate the crucial part of the MESS. Further experiments are needed for a better overview on the performance of the MESS.

The performance of the PIM can be increase by using a more advanced controller. Experiment on the paper pick-up method should be performed to reduce the change of double sheets.

The described calibration method should be repeated with the motioned adjustments. The results increase the accuracy of the positions and performance of the actuators and sensors.



## Appendix I Requirement analysis

This appendix is an extension to the analysis described in the main part of the thesis. It contains the steps that were taken but left out in the main part of the thesis.

### Application tests

The starting point of the requirement analysis is the application tests.

First a list of test that it should be able to perform without making any major changes to the setup:

5. Emulating part of a realistic paperpath with a single controller.
6. Emulating part of a realistic paperpath with a distributed controller.
7. Test the influence of the number of sensors. Determine the minimal amount of sensors, the optimal amount of sensors and the maximum amount of sensors that only decreases the performance.
8. Test the influence of the connections of sensors and actuators to the controllers. For instance, use a sheet detector near to an earlier pinch to control an actuator.
9. Test the influence of the number of motors connected to 1 controller.
10. Test the influence of the connections of the sensors to the controllers. For instance, test if it is possible to connect all sheet detectors to 1 controller.
11. Test the influence of the placement of the sensors. For instance, test the minimal, optimal and maximal distance between the sheet detectors and the pinches.
12. Test the use of different types of motors. More / less powerful, linear or step.
13. Test impact on longer running times. Determine if the longer running affect the setup.

Secondly a list of test that could be nice to perform but are not really necessary:

14. Test the transportation of larger paper. This way the paper is present in more than two pinches at ones.
15. Test the influence of the placement of the pinches.
16. Test the influence of the placement of the motors (direct or belt driven).
17. Test impact of the insertion of paper under an angle.

Next to these test there is another aspects to consider. As stated before, the setup is part of a HIL simulation. Therefore it should be easy to connect and disconnect the PASS from the ECS. In the Boderc project the MESS is used at different locations. Therefore it is required that the MESS must fit inside a "normal" car. This limits the maximum size and weight of the PASS.

These test are use to determine the characteristics of the PASS. Table 11 gives an overview of the impact of the test on the characteristics.

Characteristic / Test number	1	2	3	4	5	6	7	8	9	10	11	12	13	Typ.
<b>Mechanical</b>														
<b>Pinches</b>														
Minimal number of pinches	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Variable pinch placement	-	-	-	-	-	-	-	-	-	-	X	-	-	?
Pinch drives														
Minimal number of drive systems	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Flexible motor mounting	-	-	-	-	-	-	-	X	-	-	-	X	-	X
Direct driven	-	-	-	-	-	-	-	-	-	-	-	X	-	?
Belt driven	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pinches connected (belt)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<b>Sensors</b>														
Minimal number of encoders	3	3	4	3	3	3	3	3	3	3	3	3	3	4
Minimal number of sheet detectors	6	6	12	6	6	6	6	6	6	6	6	6	6	12
Variable placement of sheet detectors	-	-	-	-	-	-	X	-	-	-	-	-	-	X
<b>PIM</b>														
Minimal number of sheets	50	50	50	50	50	50	50	50	200	50	50	50	50	200
Variable skew	-	-	-	-	-	-	-	-	-	-	-	-	X	?
Variable size of sheets	-	-	-	-	-	-	-	-	-	X	-	-	-	?
Smallest inter sheet distance of paper (mm)	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Maximum inter sheet distance of paper (mm)	50	50	50	50	50	50	50	50	50	50	50	50	50	50
<b>Interfacing</b>														
Flexible connections	-	-	-	X	X	X	-	-	-	-	-	-	-	X
<b>Performance</b>														
Pages per minute (PPM)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Maximum acceleration (m/s <sup>2</sup> )	49	49	49	49	49	49	49	49	49	49	49	49	49	49
*X* Characteristic is needed for that test														
*?* Characteristic that is optional														
*-* Characteristic is not important for that test														

Table 11 - Characteristics vs. tests

All tests should represent a realistic part of a paperpath. When a characteristic isn't important the value of the first test is used since this represent a test of a realistic paperpath. The values in the typical (Typ.) column describe the minimal required values of the characteristics. This is determined by the maximum value of a characteristic of the required tests. The values of the optional tests are not used as a requirement value.

### Characteristic summary

Table 12 gives an overview of the requirements. In this table an extra column is added which gives an indication of the importance of a characteristics and the impact the characteristic has on design decisions. The following sections will elaborate on the characteristics of this table. These sections will only elaborate on the meaning and importance of the characteristics and will not contain design choices. The design choices can be found in the main part of the thesis.

Characteristic	Value	Importance for design				
		1	2	3	4	5
<b>Mechanical</b>						
<b>Pinches</b>						
Minimal number of pinches	3					X
Variable pinch placement	?					X
Pinch drives						
Minimal number of drive systems	3				X	
Flexible motor mounting	X					X
Direct driven	?			X		
Belt driven	X			X		
Pinches connected (belt)	-	X				
<b>Sensors</b>						
Minimal number of encoders	4			X		
Minimal number of sheet detectors	12			X		
Variable placement of sheet detectors	X					X
<b>PIM</b>						
Minimal number of sheets	200					X
Variable skew	?			X		
Variable size of sheets	?			X		
Smallest inter sheet distance of paper (mm)	10			X		
Maximum inter sheet distance of paper (mm)	50			X		
<b>Interfacing</b>						
Flexible connections	X					X
<b>Performance</b>						
Pages per minute (PPM)	100				X	
Maximum acceleration (m/s <sup>2</sup> )	49				X	
<b>Dimensions</b>						
Size						
Maximum width	150 cm			X		
Maximum depth	50 cm			X		
Maximum height	40 cm					X
Maximum weight	70kg			X		
<b>Costs</b>						
	-					
*X* Characteristic that is needed for basic functionality / Selected column						
*?* Characteristic that is optional						
*-* Characteristic that is not important						

Table 12 - Characteristic summary

The next section elaborate on the characteristics of this table

## Pinches

The pinches are an important aspect of the PASS. The amount and position of the pinches determine the size and complexity of the design. To be able to simulate a realistic part of a paperpath at least three pinches are needed. One as part of the PIM to speedup the paper and two pinches to perform a control action. Not only the amount of pinches but also the placement has a great impact on the design. This will influence the choice on the frame type and the way the pinches are connected to the frame. The drive system is another aspect that influences the design. The way the drive is connected to the pinches and the frame will be quite different if it should be easy to switch a motor or change the type of drive

## Sensors

The number of sensors that are needed have a limited impact on the design. Sensors are small and easy to mount. The variable placement of the sensors has a greater impact on the design. If the placement should be variable there should be an easy way to change the position and fix the sensors in the new position.

**PIM**

There are several aspects that influence the design of the PIM. The PIM must be able to contain a certain amount of paper sheets which are fed to the paperpath one at the time. To be able to run for a few minutes at least 200 sheets are needed. This way tests could be performed for 2 minutes at top speed. Much more paper sheets results in other difficulties. When the number of paper sheets becomes larger (more than 400) the design becomes more complex and the PIM will increase in weight and size. The variable size and skew have also an impact on the design but these options are not needed.

**Interfacing**

The only aspect that influences design choices of the interfaces is the flexible connections. The flexible connection should make it easy to change the position of the actuators and sensors. This way it is easy to switch to a different test.

**Performance**

The performance of the PASS influences the design. The performance has a great impact in the choice of the motor. The PIM and output tray must also be able to handle paper sheets at the required speed. The required speed by the Boderc project is 60 PPM. To be able to perform future experiments the minimal operating speed will be 100 PPM

**Dimensions**

The dimensions of the PASS are not important for design decisions. The dimensions are limited by the requirement that it must be possible to transport the MESS in a “normal” car. The dimensions in the table are an estimation of the maximum dimension. When the setup is within these boundaries it is possible to fit the PASS and the other components of the MESS in a car. The maximum weight is related to the weight that two people can carry. Because the PASS should be quite stiff the weight might reach its limit and therefore influences design choices.

**Costs**

The budget for this project was estimated for an out-door production but will be produced in-house. Because of this the limitation of the costs are not an important design aspect. When a decision does not influence the performance the cost will be the decisive factor to keep the costs low.

## Appendix II Motor and gear selection

This appendix is an extension to the motor and gear selection in the main part of the thesis. This appendix contains the detail of the simulations that were performed. Also the optimization method used to determine the optimal gearing is described in more detail.

### Simplified pinch model

To have a good representation of the real setup measurements on the PASS were performed. The results of these measurements are summarized. Calculations on these measurements are included in this overview. The requirements are used to determine the highest average speed and the maximum acceleration of the motors.

Measurements & Calculations	
Used formula	
Inertia	$I = 0.5 * m * r^2$
Used abbreviations	
wc - worse case	
Bearing of the top and bottom roller (8x)	
mass	= 12,0 [gram]
r (outside)	= 11mm
I	= $0.5 * 0.012 * 0.0011^2 = 7,26 * 10^{-9}$ [kg.m <sup>2</sup> /rad].
8 * I	= $58,08 * 10^{-9}$ [kg.m <sup>2</sup> /rad]
Resistance	= ????
Axel of the bottom roller (2x, biggest)	
Weight	= 194,5 [gram]
Diameter	= 8,0 [mm] (axel only)
Length	= 393,5 [mm]
I	= $0.5 * 0.1945 * 0.004^2 = 1,56 * 10^{-6}$ [kg.m <sup>2</sup> /rad]
2 * I	= $3,11 * 10^{-6}$ [kg.m <sup>2</sup> /rad]
Paper	
Weight	= 5.06 [gram]
Length	= 297 [mm]
Width	= 210 [mm]
Requirements	
Pages per minute	= 100
Space between pages	= 50 [mm]
Displ. per minute	= $100 * (210 + 50) = 26000$ [mm]
Min. max. Paper speed	= $26 / 60 = 0.433$ [m/s]
Max. acceleration (5g)	= $49.0$ [m/s <sup>2</sup> ] ( $g=9.80665$ m s <sup>-2</sup> )

The values of the measurement are all calculated for two pinches. In two pinches there are 8 bearings in total. Two on each top roller and two on each bottom roller. The axel of the top rollers is fixed. Only the bearing and a small plastic cover rotate. Because of this there are no additional calculations for the top roller. The inertia of the bearing is 100 times smaller than that of the axels. Therefore this inertia is neglected. The resistance of the bearing is unknown. Test from Océ showed that this resistance has a smaller impact on the system than the inertia. This knowledge is used to determine the resistance by simulation.

Figure 27 shows the model that was used during the simulations.

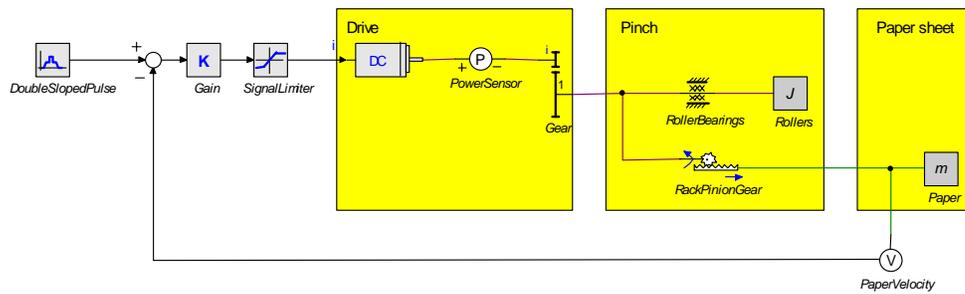


Figure 27 - Simplified pinch model

The parameters and simulations setting of the model are listed below.

Parameters	
Rollers\J	3.112e-006 {kg.m <sup>2</sup> /rad}
RollerBearings\d	0.0005 {N.m.s/rad}
ServoMotor\P_max	20 {W}
Gear\i	-1
Paper\m	0.005 {kg}
RackPinionGear\radius	0.0139 {m}
RackPinionGear\rack_length	2 {m}
Gain\K	100
SignalLimiter\minimum	-30
SignalLimiter\maximum	30
DoubleSlopedPulse\start_time	1 {s}
DoubleSlopedPulse\stop_time	4 {s}
DoubleSlopedPulse\max_start	2 {s}
DoubleSlopedPulse\max_stop	3 {s}
DoubleSlopedPulse\amplitude	0.217
DoubleSlopedPulse\max_amplitude	0.433
DoubleSlopedPulse\slope1	24.5
DoubleSlopedPulse\slope2	49
Initial Values:	
Rollers\phi_initial	0 {rad}
ServoMotor\rate_int_initial	0
ServoMotor\p.omega_initial	0 {rad/s}
ServoMotor\phi_initial	0 {rad}
Paper\x_initial	0 {m}
RackPinionGear\x_initial	0 {m}
Run Specifications	
StartTime:	0
FinishTime:	5
Event Delta:	1e-006
Integration Method:	
MeBDFiMethod	
Absolute Tolerance:	1e-007
Relative Tolerance:	1e-007
Algebraic Loop Absolute Tolerance:	1e-007
Algebraic Loop Relative Tolerance:	1e-007
Use Fixed Step Size:	FALSE

The gearing in this model is negative. This is the result of the used component. This gearing inverts the rotation. The Servo motor has a lot more parameters which are not included in this overview. The parameters are set by the Servo motor editor. The resistance of the bearing was determined by simulating with a bearing resistance of 0. In this case there is no resistance in the model and the peak power can be found at the maximum accelerations. After this the bearing resistance was increased until the consumed power during the constant velocity equals the peak power of this first simulation. The results of this simulation are presented in Figure 28.

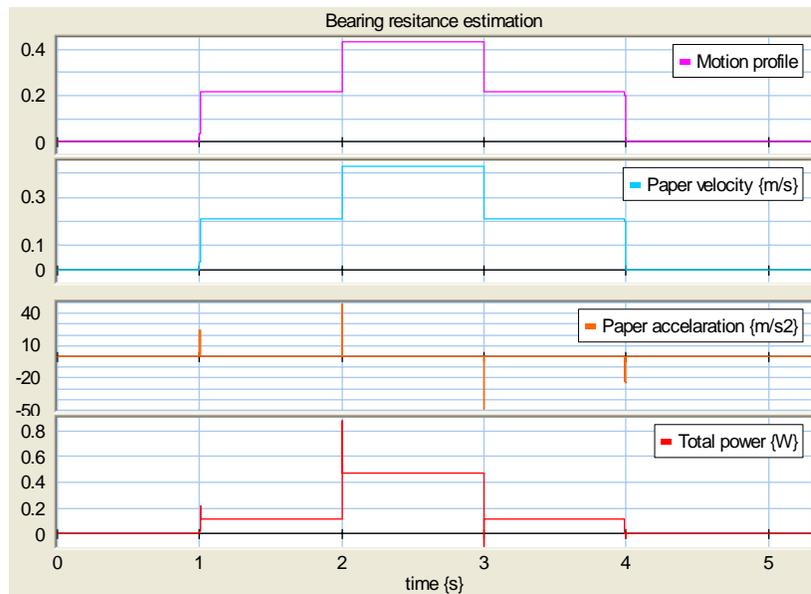


Figure 28 - Simulation result (bearing resistance)

The result of this estimation was a bearing resistance of 0.500 [mN.m.s/rad]. This estimation was doubled to ensure a motor that is powerful enough.

**Motor selection**

The motor selection was performed with the model described in the previous section. The same parameter and simulation settings were used with the exception of the bearing resistance and the motor. The bearing resistance was set to 1,00 [mN.m.s/rad]. There were three different simulation performed with each a different motor. These motors are selected with the Servo Motor Editor. The motors that were simulated are:

- Maxon RE25 10W
- Maxon RE25 20W
- Maxon RE30 60W

All motors were capable of meeting the requirements. The interesting aspect of the motor selection is the performance the motor. A torque speed plot and a temperature plot were used to analyze the performance. The torque speed plot contains information about the maximum operating modes, overheating threshold, efficiency and the results of the simulations. The temperature plot contains information about the temperature of the coil and the housing. The results of one of the simulations are include in the figure add the end of this appendix. Next to this simulation this picture shows the result from simulations with different gear ratios.

**Gear selection**

All motors have a certain working area. This working area is defined by a certain amount of torque and speed. In most applications an amount of gearing is needed to ensure that the motor is in its working area during normal operation. First the amount of gearing was investigated with the motor characteristics. The characteristics that were investigated are the maximum velocity and torque. The results are represented in Table 13.

Motor type	Velocity 31,2 [rad/s]		Torque 0,044 [N]	
	Maximum	Nominal	Minimal	Nominal
Maxon RE 25 10 W	0,054	1,034	2,932	0,659
Maxon RE 25 20 W	0,027	0,517	5,523	0,636
Maxon RE 30 60 W	0,036	0,695	24,318	2,273

Table 13 - Maximum and nominal gearing

The velocity is the velocity of the roller at 100 pages per minute with a space between to paper sheet of 5 cm. The torque is the maximum amount of torque that was needed in the previous simulation. Here the minimal amount of gearing is larger than 1. This is because the all motors are capable of delivering enough torque without gearing. These results indicate that gearing is not really necessary but it could increase the performance of the motor. The nominal amount of gearing for the Maxon RE 25 20 is near the gear ratio of the belt drive gearing. The belt drive gearing is the gear ratios as a result of the belt drive of the pinch which is explained in the main part of the thesis. Further investigation is needed to see if this gearing is enough.

After this first investigation the 20-Sim multiple run mode was used determine the optimal amount of gearing. This was done by sweeping the gear ratio from 1 to 1/100 with 100 steps and optimizing with the Integral Square Value method. The steer signal of the motor is used as a representation of the amount of power that is used by the motor. The Integral Square Value (ISV) method was used to add an extra penalty to a high steer signal. A high steer signal would require more powerful amplifiers which is an unwanted result. The results of the simulations were exported to excel which was used to generate a chart of these results. This chart is presented in Figure 29.

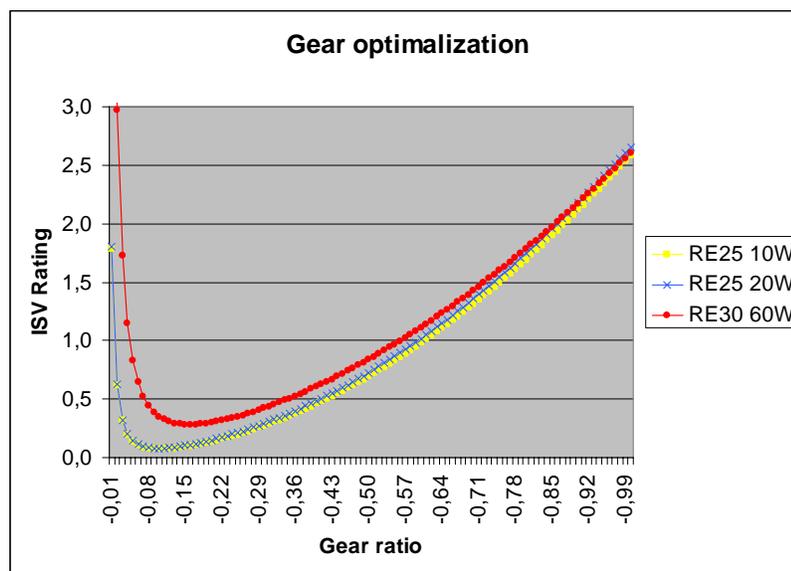


Figure 29 - Gear optimization

One aspect of this experiment can be seen clearly. With high gearing (0.01) the velocity of the motor exceeds the maximum velocity. This results in very high values for the ISV Rating. After the gear ratio is within the allowed region the ISV Rating drops and then gradually increases. This figure shows that the 10 and 20 Watt motors show an almost identical behavior. This experiment was repeated with a different motion profile. This influences the results. The steepness of the rising line changes because of this. The main shape of the figure and the optimal gear ratio do not change much.

### Final choice

Based on the findings of the earlier described simulations additional simulations were performed to determine which motor is most suitable. For all three types of motors three simulations were performed. All simulation use the same model and parameters but with different gear ratios. The chosen gear ratios are no gearing, optimal gearing and belt drive gearing. Figure 30 show the results from the simulations with the Maxon RE25 20 Watt motor. This is the motor which was selected as best choice.

The gear ratios are:

- No gearing: -1.00
- Optimal gearing: -0.100
- Belt drive gearing: -0.486

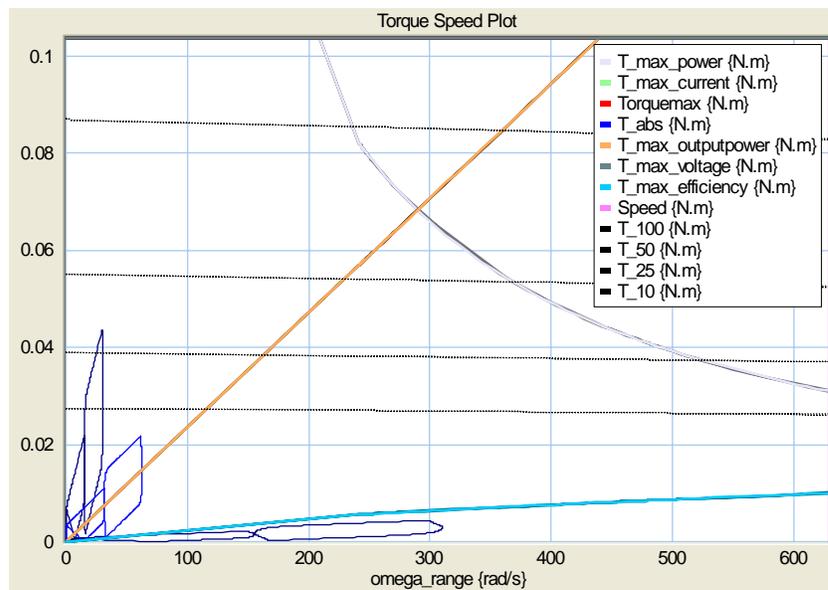


Figure 30 - Simulation results of motor and gear selection

The lines in the bottom left corner of Figure 30 shows the simulations results. From left to right these are no gearing, belt drive gearing and optimal gearing. Without gearing the motor is completely outside the working area of the motor. It crosses the  $T_{100}$  and  $T_{50}$  lines which indicate that the motor could overheat if it has to perform at this level. The belt drive gearing performs better. It partly located in the working area of the motor and does not cross the temperature lines. With this type of gearing the motor should be able to reach the requirements. The optimal gearing is situated beneath the maximum efficiency line. This gearing is better because it still has a lot of margin to the maximal values. A disadvantage is the extra gearing that is needed.

The choice was made to use five Maxon RE25 20 Watt motor. Because the simulations indicated that the belt drive gearing is sufficient four of these motor are without extra gearing. To be able to test the impact of this extra gearing one motor has extra gearing. Together with the belt drive gearing the total gearing is about the same as the optimal gearing.

## Appendix III Construction document

### Introduction

This appendix detailed description of the mechanical design of the PASS. This document can be used to reproduce parts of the PASS. The construction was done in cooperation with Dutch constructors. The remainder of this document is written in Dutch. The order list are included on the bottom of this appendix.

### Inleiding

In dit document staan de beschrijvingen van de onderdelen voor het papierpad beschreven. De maten kloppen wel maar tijdens constructie ontstaan er vaak afwijkingen waardoor sommige onderdelen beter apart uitgelijnd kunnen worden. Als dit het geval is staat het erbij.

Algemene aandachtspunten:

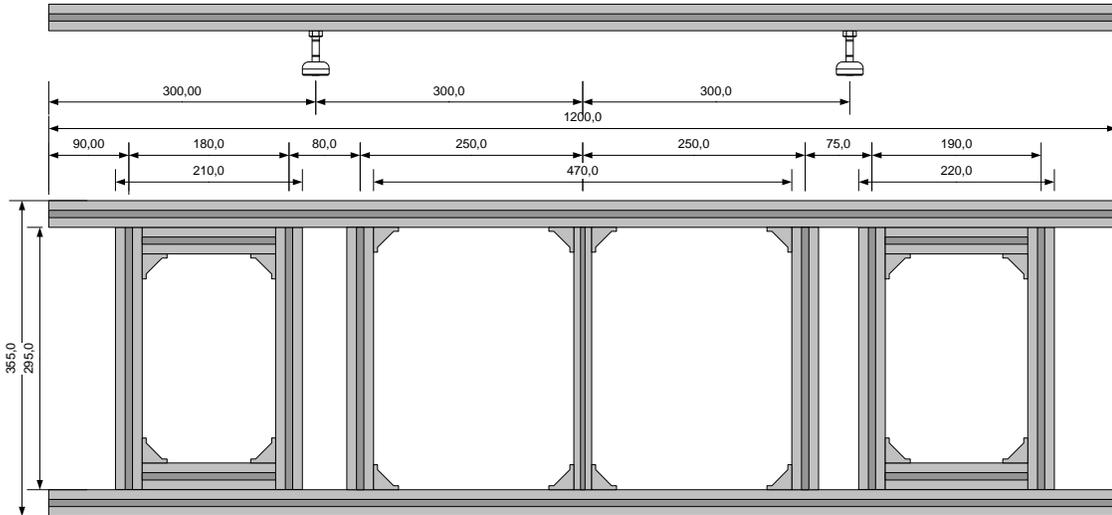
- Dikte van materiaal is niet altijd heel constant (vooral plexiglas)
- Meet altijd vanaf 1 kant en bij alle onderdelen vanaf dezelfde kant. Eventuele afwijkingen blijven hierdoor beperkt (zagen is meestal niet zo nauwkeurig). Meet plaatjes voor de achterkant dan vanaf de andere zijde (plaatjes zijn in spiegelbeeld gemonteerd).
- Vaak kan het boren ook in de freesbank, dit is meer werk maar meestal preciezer. Bij grotere aantallen is het weer minder werk, scheelt namelijk aftekenen van alle onderdelen afzonderlijk.

Aanbevelingen

- Nakijken hoogte knepen. Het maximaal aantal vellen ligt nu op 250 door de beperkte pinch hoogte, wanneer er meer vellen nodig zouden zijn dan moet de kneep hoger geplaatst worden. Bijkomend voordeel is de extra ruimte voor de motoren (is nu vrij krap).

## Profile Base

Alle componenten voor de base kunnen op maat besteld worden. Hierna kan alles in elkaar geschroefd worden en is de base klaar.

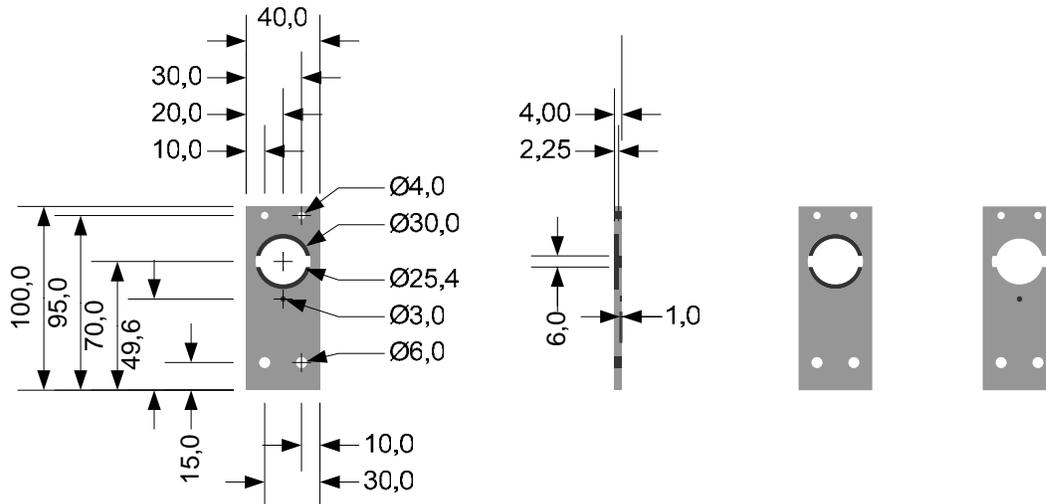


## Pinch constructie - onder bevestiging

### Constructie beschrijving (8x)

1. Aluminium plaat
  - a) Zagen 100,0 x 40,0 x 4,0 mm
2. Bevestiging boven plaat
  - a) Boren 4 mm
3. Bevestiging profiel
  - a) Boren 6 mm
4. Onder pinch gat
  - a) Draaibank
    - Groot gat boren 23 mm
    - Gat uitfrezen 25,4 mm
    - Rand uitfrezen 30,0 x 2,25 mm
  - b) Freesbank 6,0 mm
    - Zijkant uitfrezen tot aan 30,0 mm rand
5. Lock gat
  - a) Boren 3 mm

### Afmetingen en resultaat

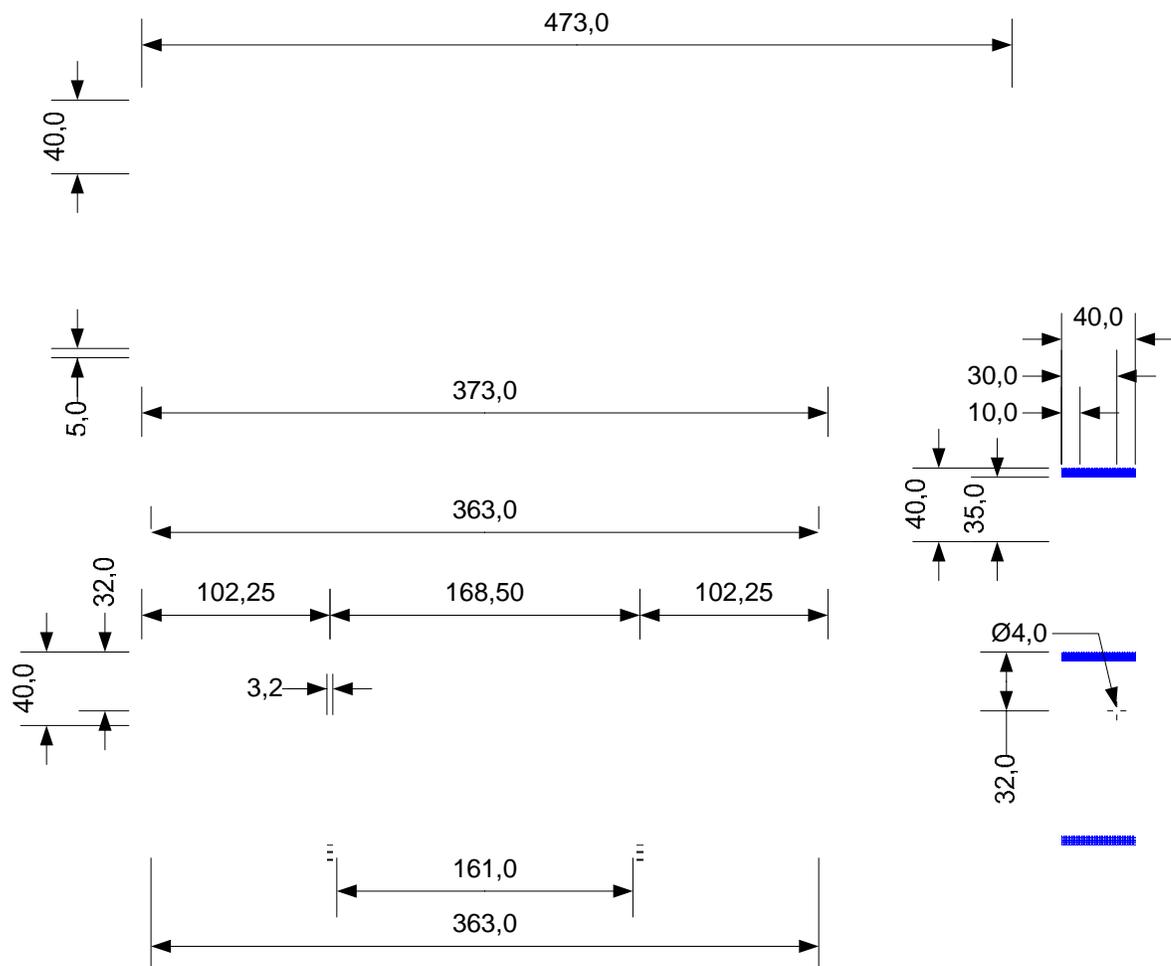


## Pinch constructie - boven bevestiging

### Constructie beschrijving (4x)

1. Plexiglas plaat
  - a. Zagen 473,0 x 40,0 x 5,0 mm
2. Onder pinch breedte
  - a. Buigen op binnenmaat
3. Pinch hoogte
  - a. Zagen vanaf bovenkant
  - b. Boren 4,0 mm
    - (uitlijnen aan de hand van indrukking boven pinch)
4. Bevestiging pinch blokjes
  - a. Boren (freesbank) 3,2 mm (3,0 mm)
    - (uitlijnen aan de hand van de breedte boven pinch)

### Afmetingen en resultaat

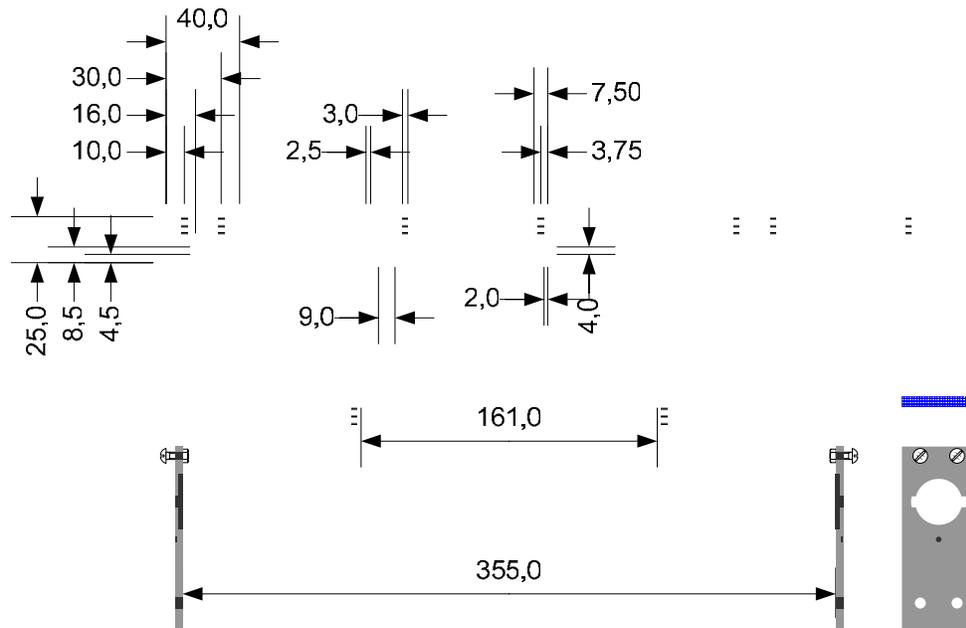


## Pinch constructie - blokje en totaal

### Constructie beschrijving (8x)

1. Plexiglas plaat
  - a. Zagen 25,0 x 40,0 x 7,5 mm
2. Bevestigen bovenplaat
  - a. Boren (freesbank) 2,5 mm
  - b. Tappen 3,0 mm
3. Bevestiging boven pinch
  - a. Freesbank 4,0 mm
    - Zijkant uitfrezen
    - (uitlijnen aan de hand van de boven pinch)

### Afmetingen en resultaat

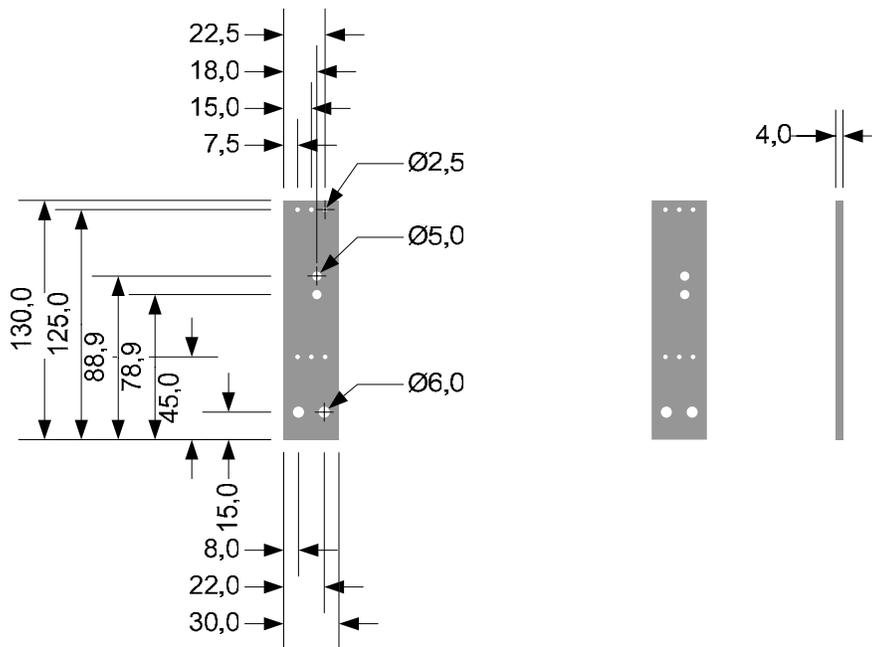


## Geleiders Constructie - zijkant

### Constructie beschrijving (4x)

- |                        |                       |
|------------------------|-----------------------|
| 1. Aluminium plaat     |                       |
| a. Zagen               | 130,0 x 30,0 x 4,0 mm |
| 2. Bevestiging platen  |                       |
| a. Boren (freesbank)   | 2,5 mm                |
| 3. Bevestiging assen   |                       |
| a. Boren (freesbank)   | 5,0 mm                |
| 4. Bevestiging profile |                       |
| a. Boren (freesbank)   | 6,0 mm                |

### Afmetingen en resultaat

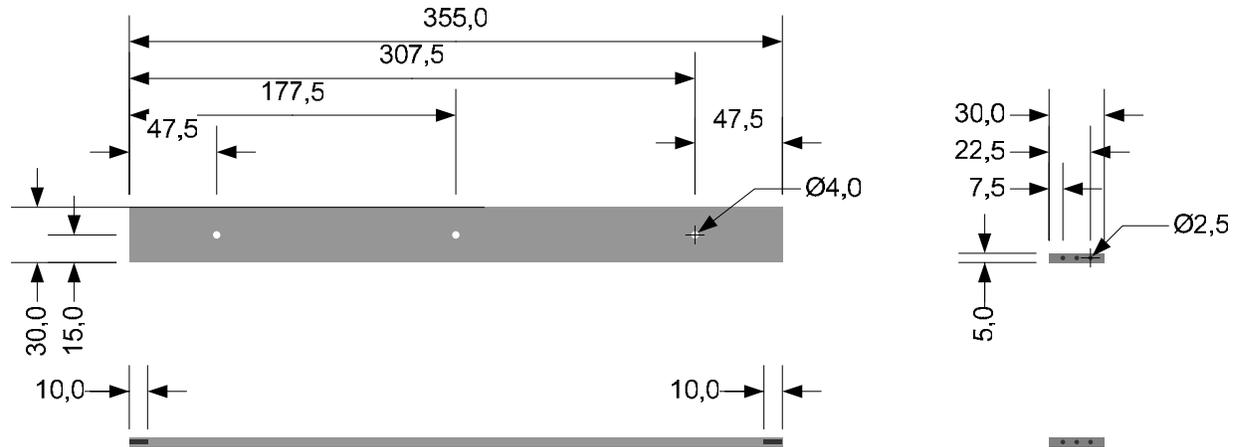


## Geleiders Constructie - platen

### Constructie beschrijving (4x)

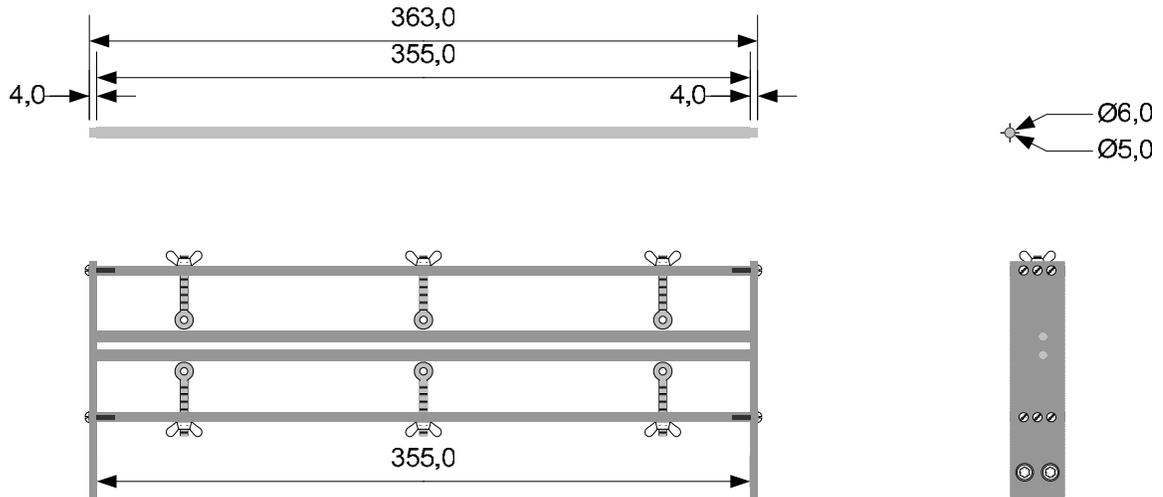
1. Aluminium plaat
  - a. Zagen 355,0 x 30,0 x 4,0 mm
2. Bevestiging zijkanten
  - a. Boren (freesbank) 2,1 mm
  - b. Tappen 2,5 mm
3. Bevestiging spanners
  - a. Boren (freesbank) 4,0 mm

### Afmetingen en resultaat



**Geleiders Constructie – assen en totaal****Constructie beschrijving (4x)**

1. Stalen as
  - a. Zagen 363,0 x 6,0 mm
2. Bevestiging zijkantenvan
  - a. Draaibank 4,0 x 5,0 mm

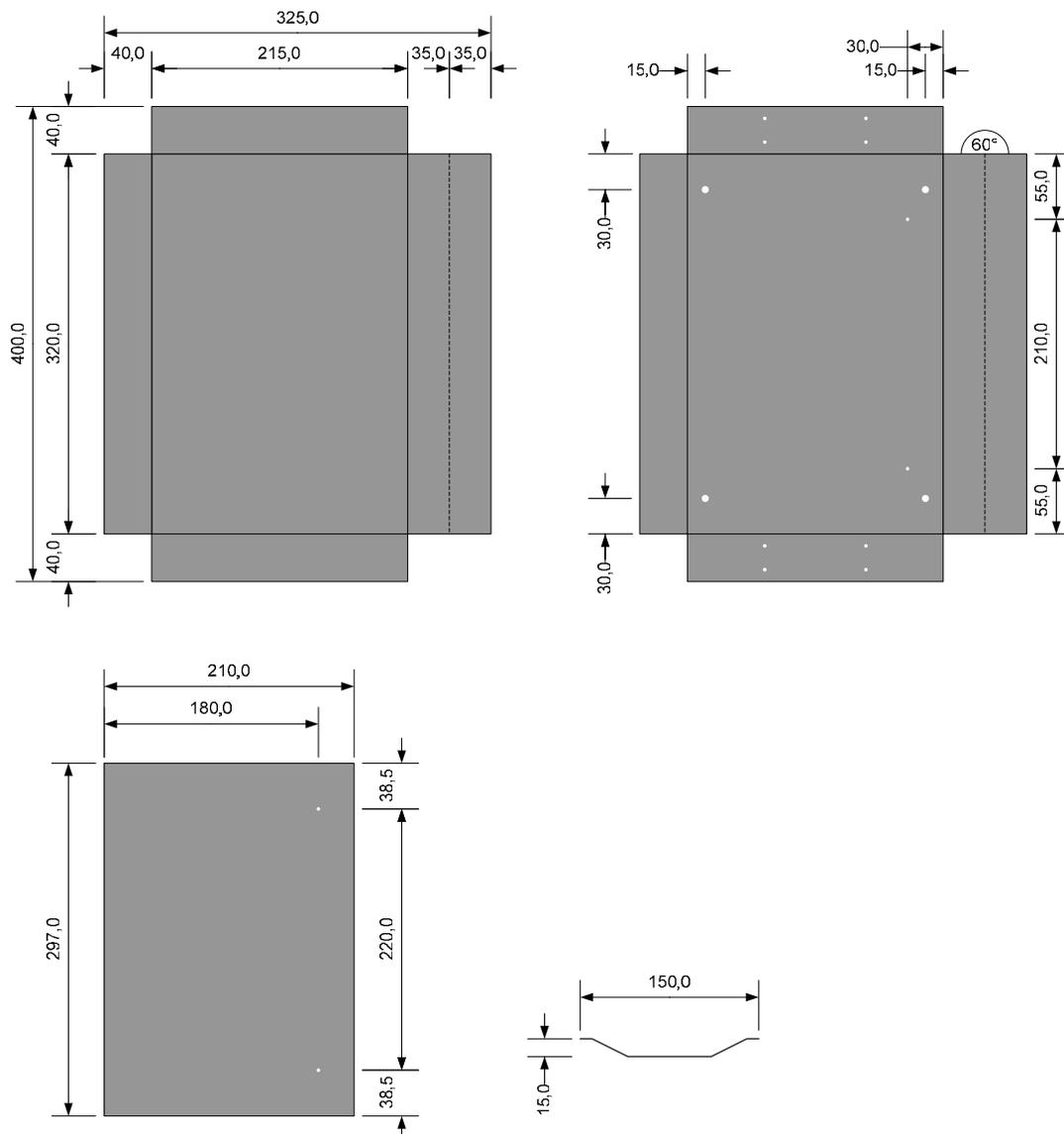
**Afmetingen en resultaat**

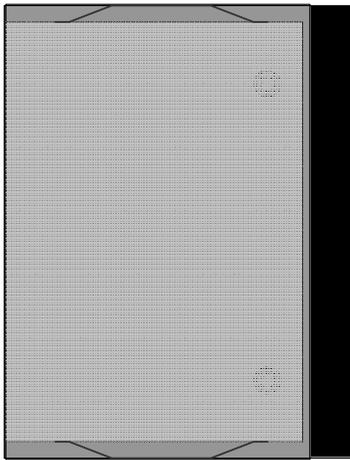
## Papier invoer - bak

### Constructie beschrijving (1x)

- |                           |                        |
|---------------------------|------------------------|
| 1. RVS plaat              |                        |
| a. Knippen                | 400,0 x 325,0 x 1,0 mm |
| 2. Bevestiging profile    |                        |
| a. Boren                  | 6,0 mm                 |
| 3. Bevestiging veren      |                        |
| a. Boren                  | 3,0 mm                 |
| 4. Bevestiging bodemplaat | 3,0 mm                 |
| 5. Invoer lip             |                        |
| a. Vouwen                 | 60°                    |
| 6. Hoeken                 |                        |
| a. Knippen                |                        |
| b. Vouwen                 | 90°                    |
| c. Lassen (TIG)           |                        |
| 7. RVS plaat              | 279,0 x 210 x 1,0 mm   |

### Afmetingen en resultaat



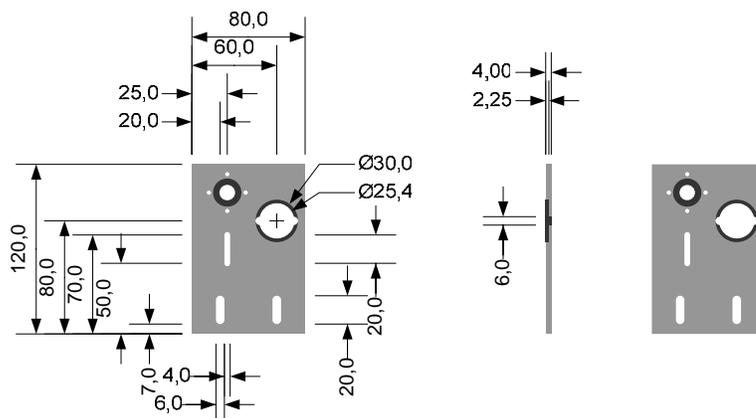


## Papier invoer- Roller mount

### Constructie beschrijving (1x)

- |  |                       |
|--|-----------------------|
| 1. Aluminium plaat                       |                       |
| a. Zagen                                 | 120,0 x 80,0 x 4,0 mm |
| 2. Bevestiging motor                     |                       |
| a. Boren                                 | 3 mm                  |
| 3. Bevestiging profile                   |                       |
| a. Frezen                                | 6,0 x 20,0 mm         |
| 4. Pinch gat                             |                       |
| a. Draaibank                             |                       |
| • Groot gat boren                        | 23 mm                 |
| • Gat uitfrezen                          | 25,4 mm               |
| • Rand uitfrezen                         | 30,0 x 2,25 mm        |
| b. Freesbank                             | 6,0 mm                |
| • Zijkant uitfrezen tot aan 30,0 mm rand |                       |
| 5. Lock gat                              |                       |
| a. Boren                                 | 3 mm                  |
| 6. Belt guide gat                        |                       |
| a. Frezen                                | 4,0 x 24,0 mm         |

### Afmetingen en resultaat



## Bestellingen

**Bestelling Boikon**

BODERC (66349)

Adres: BOIKON B.V.  
Kapteynlaan 13  
9351 VG LEEK

Tel.: 0594-517524  
Fax: 0594-517549  
E-mail: [info@boikon.nl](mailto:info@boikon.nl)  
Internet: [www.boikon.nl](http://www.boikon.nl)

ID	Nr	Description	Order nr	Length mm	Price	Total price
					€	€
1	2	Alu Profile 30 x 30 sleuf 8 mm	13000	1200	8,52	17,04
2	6	Alu Profile 30 x 30 sleuf 8 mm	13000	295	2,09	12,57
3	1	Alu Profile 20 x 20 sleuf 5 mm	12000	295	1,36	1,36
4	12	Alu hoekst. 20x28x28+centr. lip, compl. Sleuf 8E	24075		2,60	31,20
5	4	Alu hoekstuk 20x28x28, compl. Sleuf 5 (1 stuks)	24006		2,30	9,20
6	4	Alu Profile 30 x 30 sleuf 8 mm	13000	200	1,42	5,68
7	4	Stelvoet 30 - M8 x 65, verzinkt (1 stuks)	45100		2,70	10,80
8	4	Dempingsring diam. 30 (1 stuks)	45400		1,05	4,20
9	4	Sleufmoer 8E - M8 (1 stuks)	22315		0,75	3,00
10	1	Hamermoer 8E - M6 (100 stuks)	22061		39,50	39,50
11	2	Laagbolkopschroef M6 x 12 (50 stuks)	20026		8,20	16,40
Totaal						150,94

**Bestelling Maxon**

BODERC (66349)

Adres: Maxon motor benelux B.V.  
De Giem 22  
NL-7547 SV Enschede

Tel.: +31 53 - 4864 777  
Fax: +31 53 - 4864 788  
E-mail: [info@maxonmotor.nl](mailto:info@maxonmotor.nl)  
Internet: <http://www.maxonmotor.nl>

ID	Aantal	Description	Order nr	Price	Total price
				€	€
1a	1	RE 25 Ø 25 mm, Graphite brushes , 20 Watt	118752	146,00	146,00
1b	1	Digital-Encoder HEDS 5540 Ø 10 mm	110511	55,16	55,16
1c	1	Planetary Gearhead GP 32 A Ø32 mm 0.75 Nm, ball bearing, Metal	166156	101,08	101,08
2a	4	RE 25 Ø 25 mm, Graphite brushes , 20 Watt	118752	146,00	584,00
2b	4	Digital-Encoder HEDS 5540 Ø 10 mm	110511	55,16	220,64
3	5	Digital-Encoder HEDS 5540 Ø 10 mm	110511	55,16	275,80
					1382,68

## Appendix IV Scenarios

This appendix contains information about the scenarios. The scenarios provide a platform for the experiment that will be performed in the Boderc project.

### Sensors and actuators

This section contains a table with all signals of the actuators and sensors off the PASS. All scenarios need to have support for all actuators and sensors listed in this table.

Signals	Dir *	Description	Connector
<b>Motor driver (5x)</b>			
Enable	o	Driver enable (not on current driver)	1 PWM
Direction	o	Motor direction	2 GND
PWM	o	PWM	3 DIR
			4 GND
<b>Quadrature encoder (5x)</b>			
QuadA	i	First quadrature channel	1 B
QuadB	i	Second quadrature channel	2 VCC
Index	i	Index pulse (Ones each turn)	3 A
			4 IDX
			5 GND
<b>Paper detector (16x)</b>			
Detect	i	Paper detected	1 VCC
			2 VO
			3 Gnd
<b>Array sensor (2x)</b>			
SCLK	i	Clock input	1 VCC
SDIN	i	Serial data input	2 CLK
SDOUT	o	Serial data output	3 IN
			4 OUT
			5 GND
* Directions are described from the controller point of view			

Table 14 - Sensor and actuator signals

### Scenarios

In this section the 6 scenarios are presented.

### Scenario 1

The PIM and pinches are all controlled by one EST.

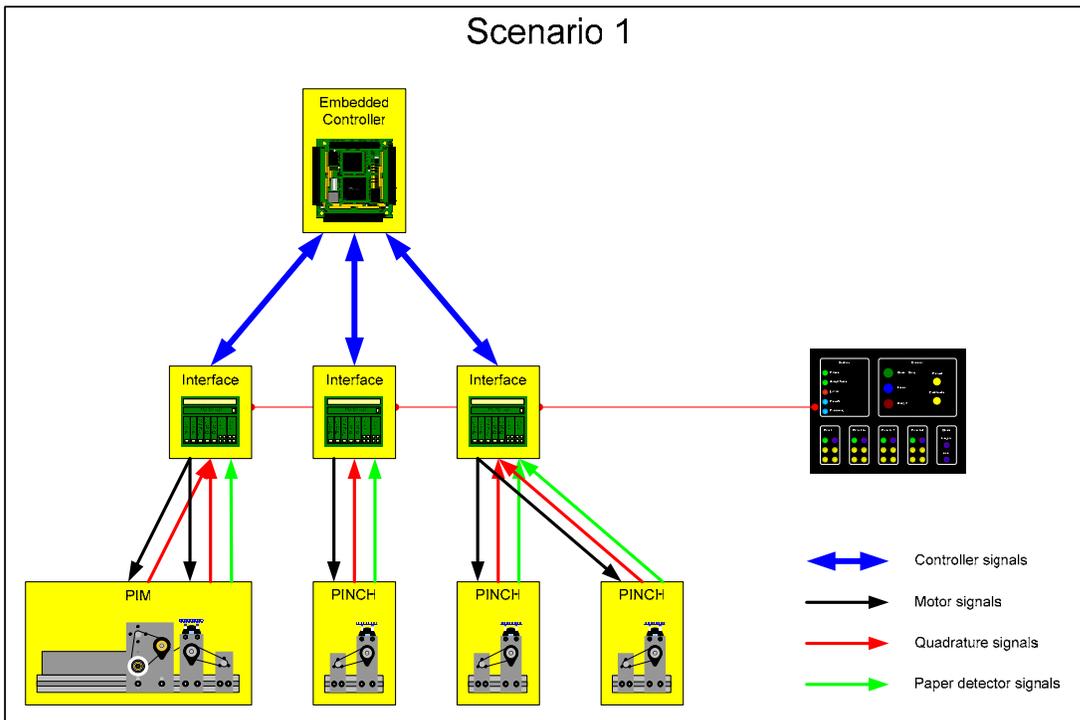


Figure 31 - Scenario 1

### Scenario 2

The PIM is controlled by one EST and all other pinches by another EST.

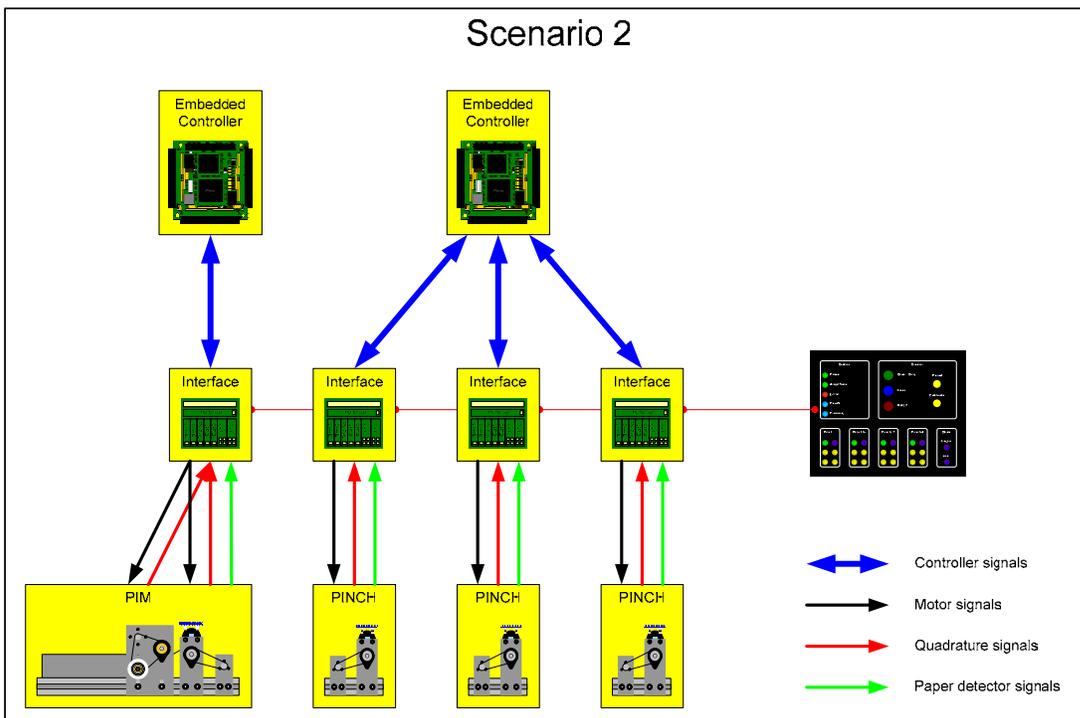


Figure 32 - Scenario 2

**Scenario 3**

The PIM is controlled by one EST and the other pinches by each its own EST.

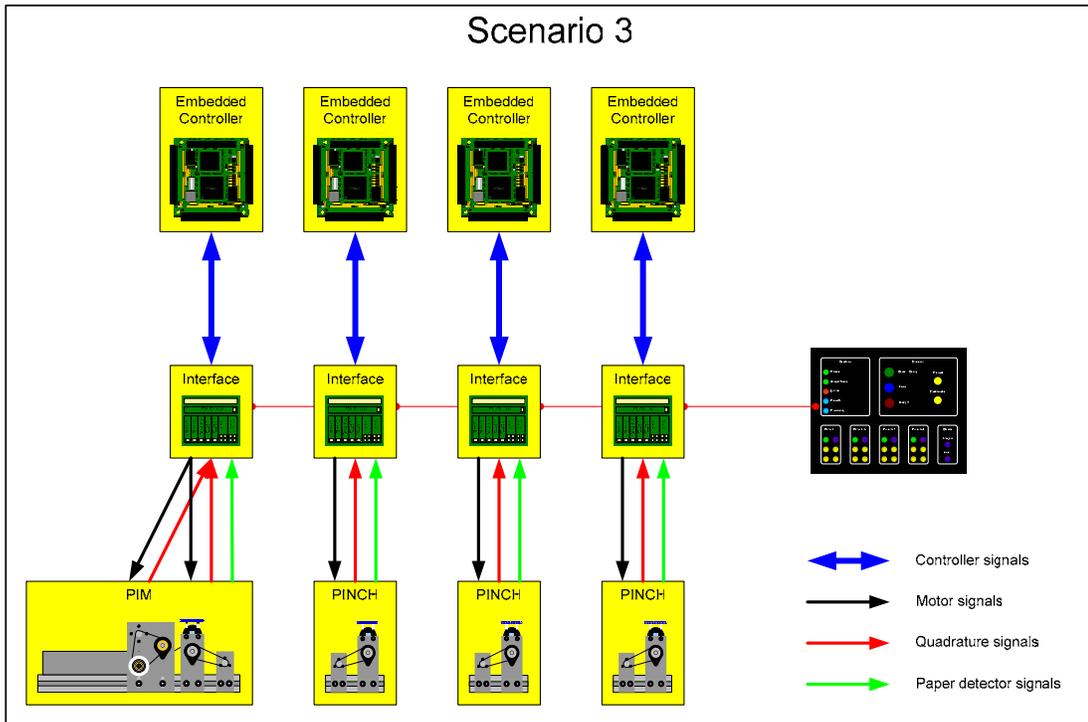


Figure 33 - Scenario 3

**Scenario 4**

The PIM is controlled by one EST, the following two pinches by one EST and the last pinch by another EST.

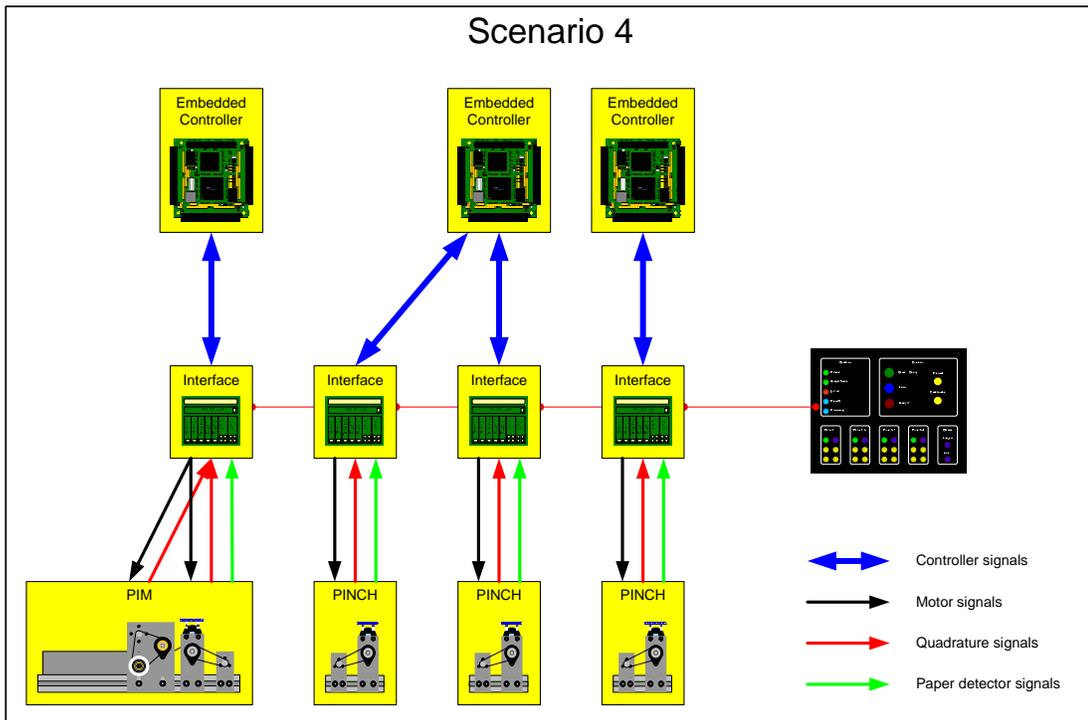


Figure 34 - Scenario 4

### Scenario 5

The PIM and the first pinch are controlled by one EST and the other two pinches by another EST.

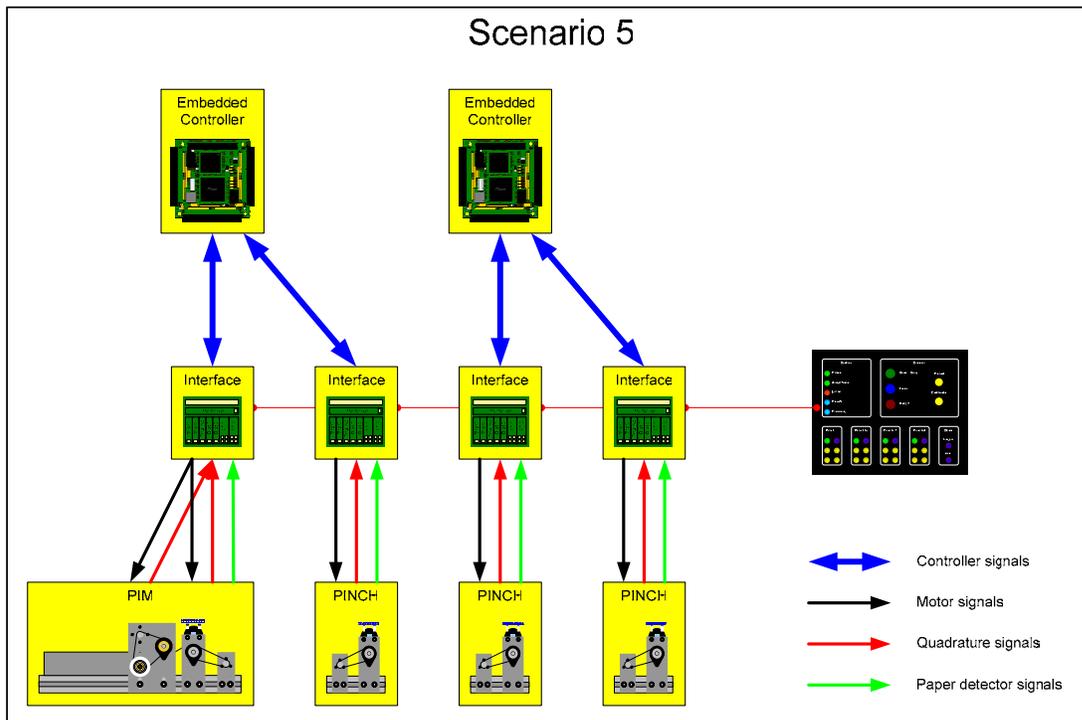


Figure 35 - Scenario 5

### Scenario 6

The PIM (including the actuators and sensors) is controlled by one EST, all motors by another EST, all encoders by another EST and all SDs by another EST.

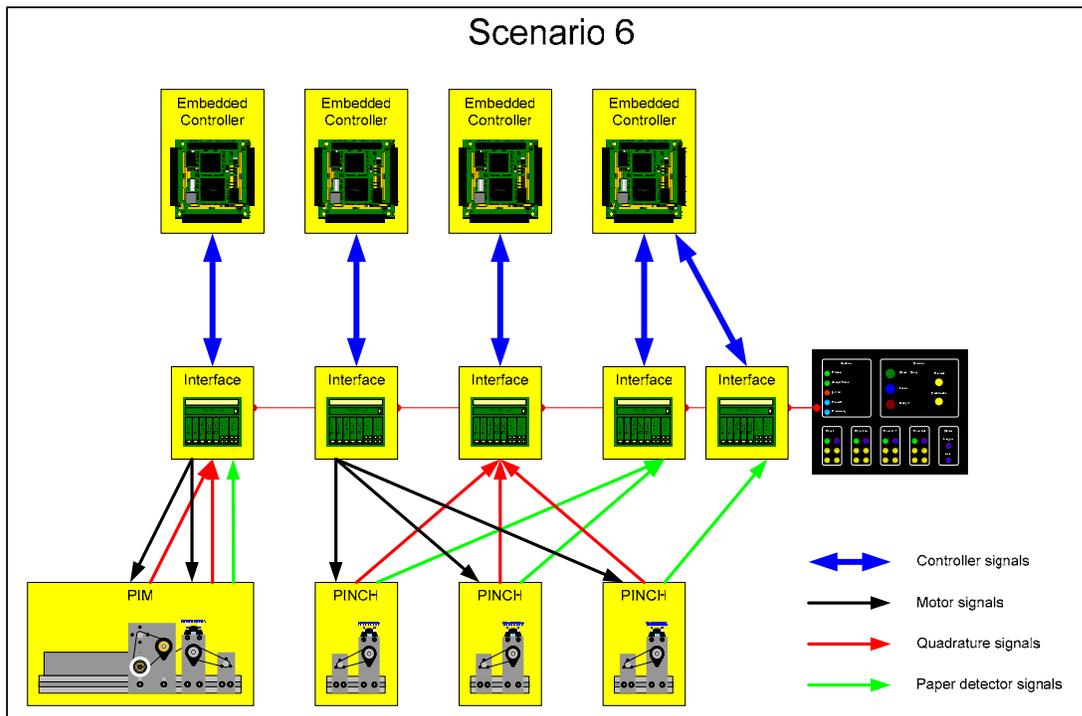


Figure 36 - Scenario 6

### Scenario and test cross reference

This section describes which scenarios can be used for which test. The tests are described in section 2.2.2.

Test / Scenario	1	2	3	4	5	6
1 Single controller	X					
2 Distributed controller			X			
3 Number of sensors		X	X	X	X	
4 Related sensors and actuators		X	X	X	X	
5 All motor 1 controller						X
6 Different connections to controller		X	X	X	X	
7 Placement of sensors		X	X	X	X	
8 Type of motors		X	X	X	X	
9 Longer run times		X	X	X	X	
10 Larger paper		X	X	X	X	
11 Placement pinches		X	X	X	X	
12 Placement motors		X	X	X	X	
13 Angle input		X	X	X	X	

Table 15 - Scenario and test cross reference

Most tests can be performed with all scenarios. For scenarios one and six the connections from the interface prints to the actuators and sensors need to be changed. In the other scenarios the connections from the interface prints to the actuator and sensors stay the same. Therefore by default the PIM and pinches have each their own interface print. This type connection is present in scenarios two to five. These scenarios will be used by default.

## Appendix V Electrical design

This appendix contains the details of the electrical design.

### Connectors

The first table shows all the connections between the Anything IO board, the connectors and the Atmel. The additional connectors are feature that are available on the Atmel.

EST connector	Actuators & sensors connectors				Control panel	Additional connectors					
	Config 1		Config 2		ATmega32	function	signals				
	function	signals	function	signals	signals						
Output	IO0	Motor 1	EN	Motor 1	EN	PD2					
	IO1		DIR		DIR	PD3					
	IO2		PWM		PWM	PD4					
	IO3	Motor 2	EN	Motor 2	EN	PD5					
	IO4		DIR		DIR	PD6					
	IO5		PWM		PWM	PD7					
	IO6	Serial	SS	Motor 3	EN	PB4					
	IO7		CLK		DIR	PB7/PB0*					
	IO8		OUT		PWM	PB5/PD0*					
IO9	IN		-	-	PB6/PD1*						
Input	IO10	Quad 1	A	Quad 1	A	PC2					
	IO11		B		B	PC3					
	IO12		IDX		IDX	PC4					
	IO13	Quad 2	A	Quad 2	A	PC5					
	IO14		B		B	PC6					
	IO15		IDX		IDX	PC7					
	IO16	PD 1	VO	Quad 3	A	PA0			Analogue (part A)	AI0	
	IO17	PD 2	VO		B	PA1					AI1
	IO18	PD 3	VO		IDX	PA2					AI2
	IO19	PD 4	VO		PD 4	VO					PA3
	IO20	PD 5	VO	PD 5	VO	PA4					
	IO21	PD 6	VO	PD 6	VO	PA5					
	IO22	PD 7	VO	PD 7	VO	PA6					
	IO23	PD 8	VO	PD 8	VO	PA7					
						PB3			Analogue (part B)	NI	
					PB2	PI					
					PC0	I2C	SCL				
					PC1		SDA				

\* Selection between SPI and U(S)ART

Table 16 - Connections table

The second table shows the connector details. This table describes the pin numbering of all the connectors.

Description			Connectors
<b>Anything IO</b>			J1
even nr	GND	Ground	
odd 1..47	IO0 IO23	General I/O	
49	VCC	Vcc (5V)	
<b>Motor driver</b>			J2, J3, J4
1	X	Blocked hole	
2	GND	Ground	
3	EN	Enable	
4	DIR	Direction	
5	VCC	Vcc (5V)	
6	PWM	PWM	
<b>Quadrature encoder</b>			J5, J6, J7
1	A	Quadrature A	
2	GND	Ground	
3	B	Quadrature B	
4	IDX	Index	
5	VCC	Vcc (5V)	
6	X	Blocked hole	
<b>Paper detector</b>			J8, ... , J15
1	VO	Ouput	
2	GND	Ground	
3	VCC	Vcc (5V)	
4	X	Blocked hole	
<b>Serial Interface</b>			J16
1	SS	Slave select	
2	GND	Ground	
3	X	Blocked	
4	SCLK	Serial clock	
5	SDOUT	Serial output	
6	SDIN	Serial input	
7	VCC	Vcc (5V)	
8	RES	Atmel Reset (active low)	
<b>Analog Connector</b>			J17
1	X	Blocked hole	
2	GND	Ground	
3	AI0	ADC Input 0	
4	AI1	ADC Input 1	
5	AI2	ADC Input 2	
6	AI3	ADC Input 3	
7	PI	Positive input	
8	NI	Negative input	
9	AVCC	Analog Vcc	
10	X	Blocked hole	
<b>Control Panel Interface</b>			J18
1	VCC	Vcc (5V)	
2	SCL	Serial clock	
3	SDA	Serial data	
4	GND	Ground	
<b>Power Connector</b>			J19
1	VCC	Vcc (5V)	
2	GND	Ground	

Table 17 - Pinning table

The next tables contain the functions of the jumpers. All jumpers are related to Atmel functions.

Jumpers (open/close)			
Name	Description	open	close
J20	Atmel Reset	disable	enabled
J24	Decouple analogue signal 0	enabled	disabled
J25	Decouple analogue signal 1	enabled	disabled
J26	Decouple analogue signal 2	enabled	disabled
J27	Decouple analogue signal 3	enabled	disabled

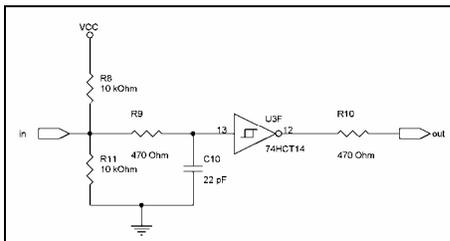
Jumpers (select)			
Name	Description	1-2	2-3
J21	Serial Interface Select	SPI	U(S)ART
J22	Serial Interface Select	SPI	U(S)ART
J23	Serial Interface Select	SPI	U(S)ART

Table 18 - Jumper settings

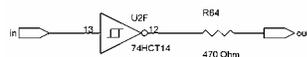
The decouple jumpers disconnect the Anything IO connector from the analogue signals. This way the Anything IO card can not interfere with the analogue input.

## Schematics

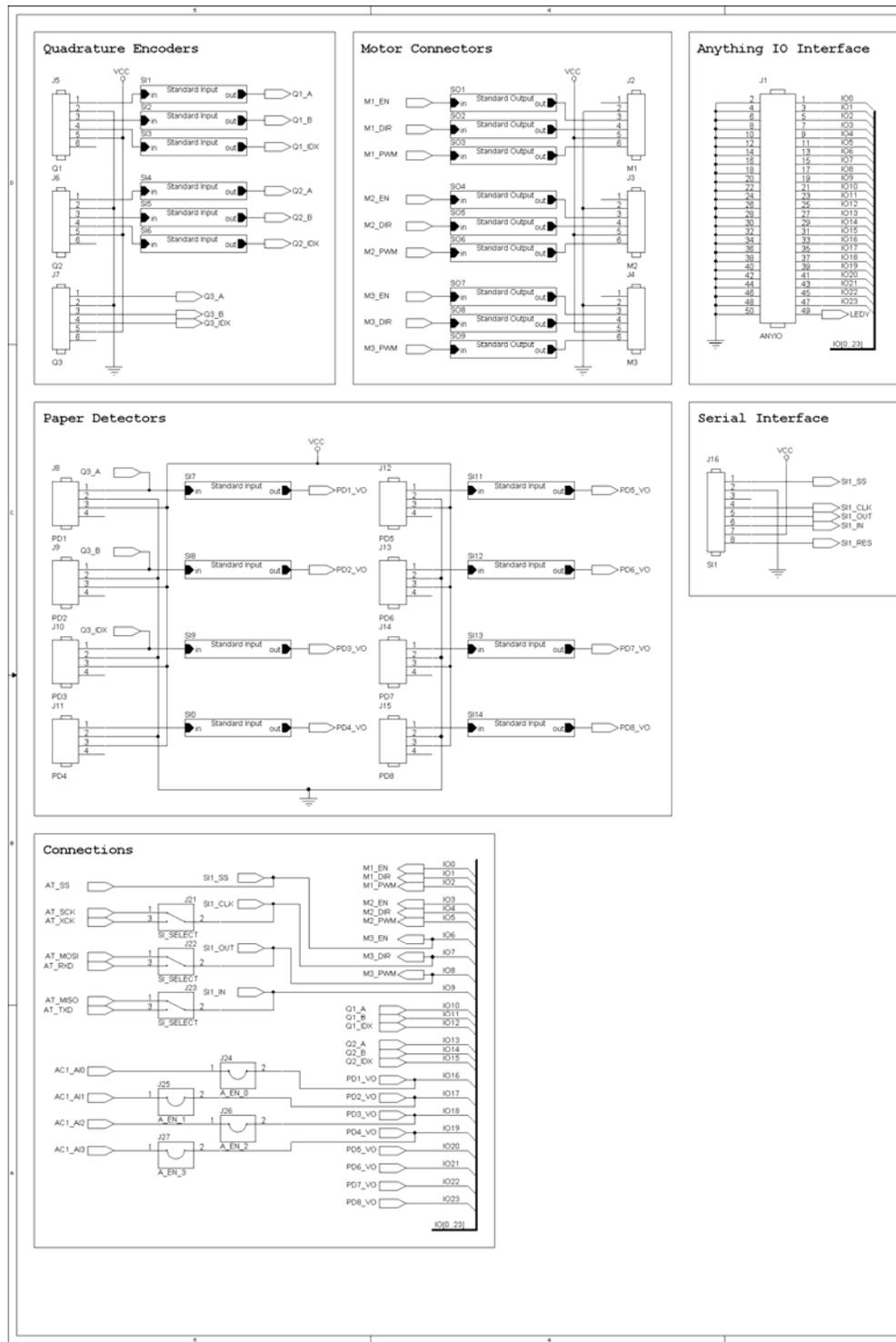
### Standard input



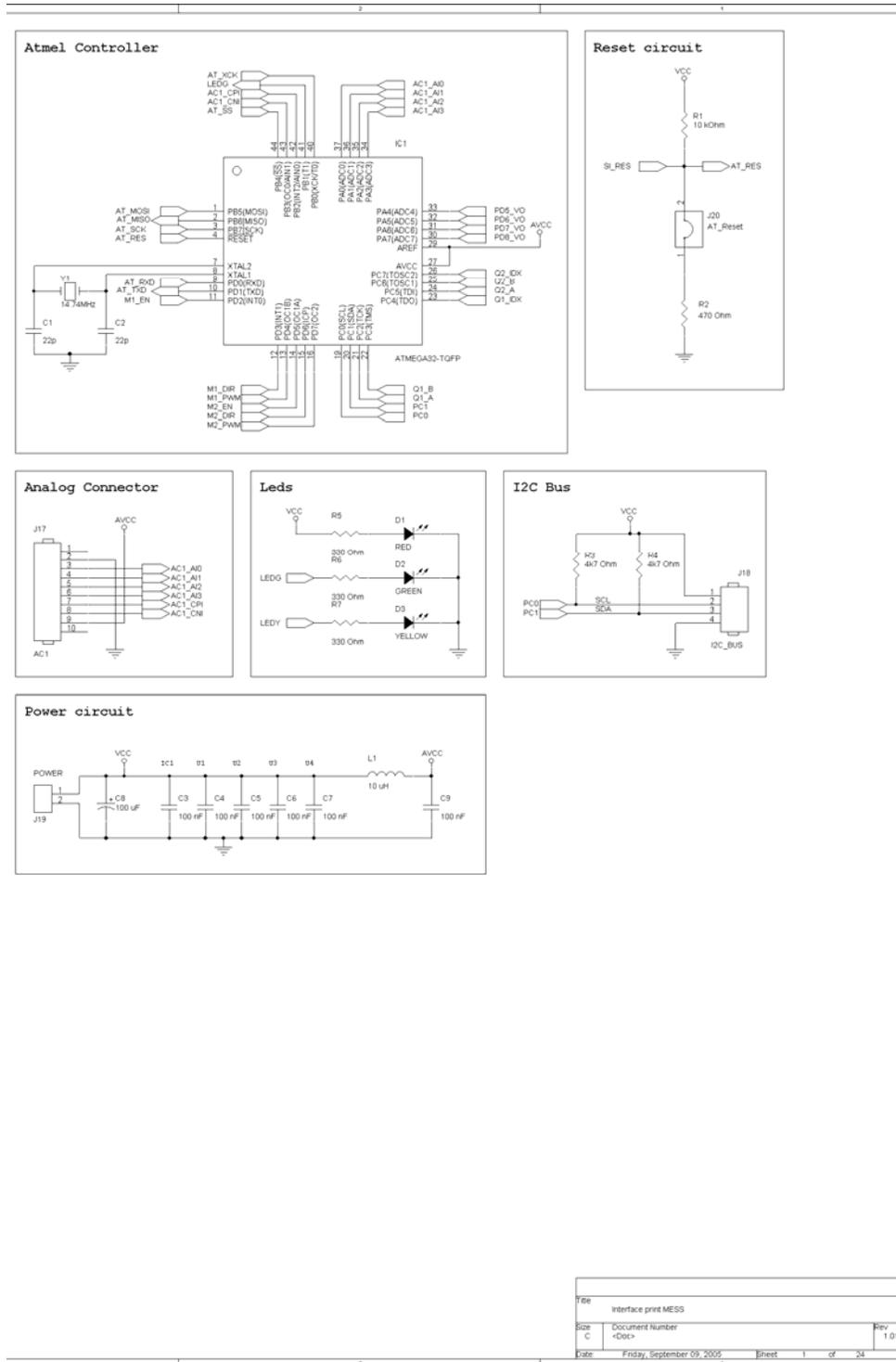
### Standard output



Main design (left part)



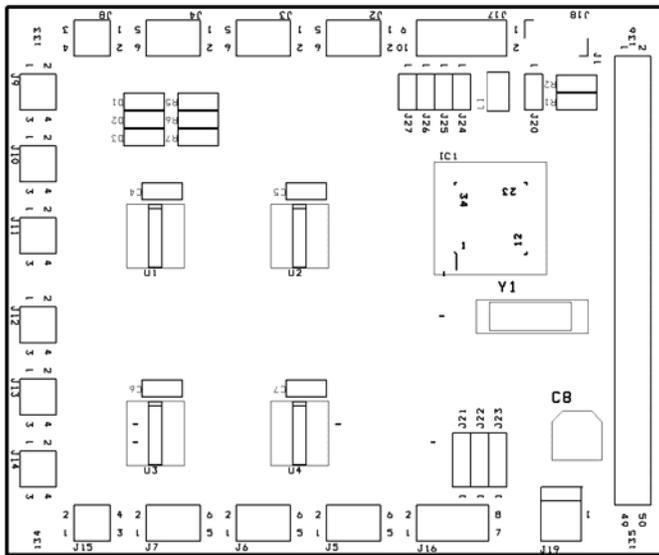
Main design (right part)



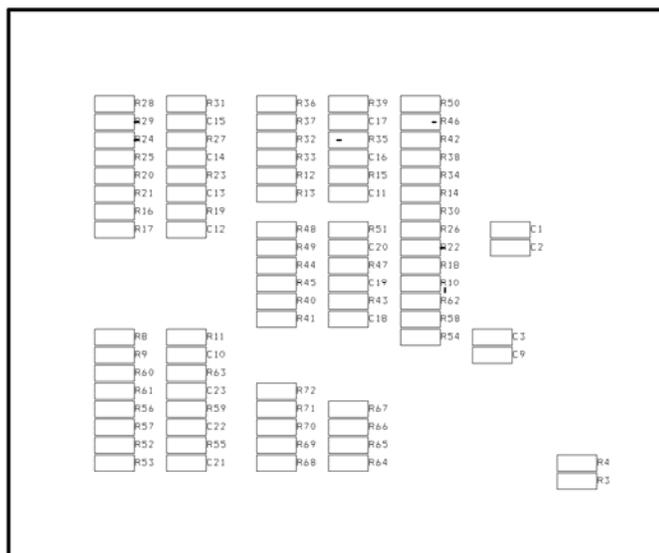
## Layout

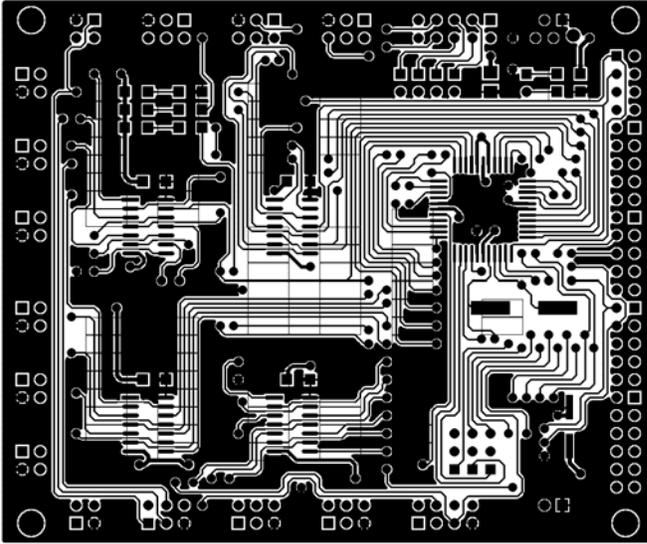
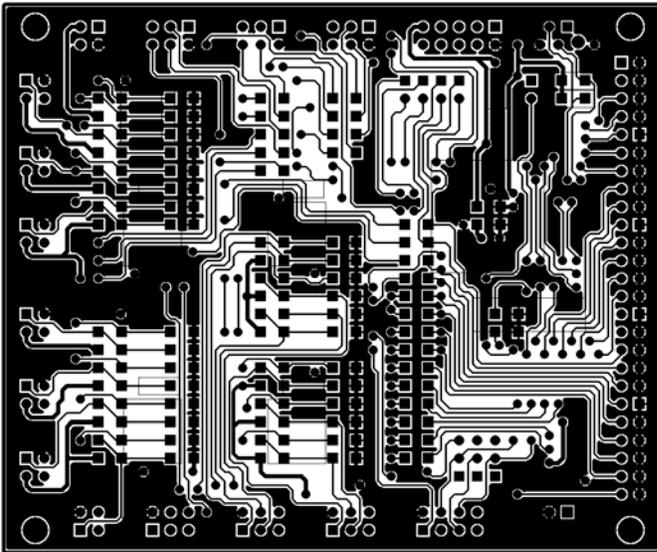
### Component layout

#### Top view



#### Bottom view



**Print layout****Top view****Bottom view**

## Component list

The next table contains the components. They are ordered at Farnell. The order numbers are included in the table.

Item	Quantity	Reference	Description	Farnell
1	2	C1,C2	Capacitor multilayer (SMD 1206) 22pF	360-6041
2	6	C3,C4,C5,C6,C7,C9	Capacitor multilayer (SMD 1206) 100nF	644-316
3	1	C8	ELCO smd WX-serie 100u	344-9993
4	14	C10,C11,C12,C13,C14,C15, C16,C17,C18,C19,C20,C21, C22,C23	Item 1	
5	1	D1	Led Red (SMD 1206)	359-9875
6	1	D2	Led Green (SMD 1206)	359-9899
7	1	D3	Led Yellow (SMD 1206)	359-9887
8	1	IC1	ATMEGA32-16AI	437-6316
9	1	J1	Male PCB Mounting box header	316-7100
10	16	J2,J3,J4,J5,J6,J7,J8,J9,J10,J 11,J12,J13,J14,J15,J16,J17	PCB Pin Strip Headers 72 Way (2.54, Gold)	77313-818-72
11	1	J18	Micro MaTch 4p female on board	148-507
12			Micro MaTch 4p male on wire	149-032
13	1	J19	2,54mm Pitch KK Con 2p	143-139
14			2,54mm Pitch KK Crimp Housing 2p	143-126
15			Crimp Terminal for 2.50 and 2.54	143-116
16	1	J20	PCB Pin Strip Headers 36 Way (2.54, Gold)	77311-818-36
17	7	J21,J22,J23,J24,J25,J26,J27	Item 28	
18	1	L1	LQH3C Inductor 10u	353-1338
19	29	R1,R8,R11,R12,R15,R16,R1 9,R20,R23,R24,R27,R28,R31 ,R32,R35,R36,R39,R40,R43, R44,R47,R48,R51,R52,R55, R56,R59,R60,R63	Resistor thick film (SMD 1206) 10 kOhm	912-591
20	38	R2,R9,R10,R13,R14,R17,R1 8,R21,R22,R25,R26,R29,R30 ,R33,R34,R37,R38,R41,R42, R45,R46,R49,R50,R53,R54, R57,R58,R61,R62,R64,R65, R66,R67,R68,R69,R70,R71,	Resistor thick film (SMD 1206) 470 Ohm	912-438
21	2	R3,R4	Resistor thick film (SMD 1206) 4.7 kOhm	912-554
22	3	R5,R6,R7	Resistor thick film (SMD 1206) 330 Ohm	912-414
23	4	U1,U2,U3,U4	74HCT14D	489-438
24	1	Y1	SM Crystal 16MHz	639-588

Table 19 - Component list

## Appendix VI FPGA Design

This appendix contains details about the FPGA design.

### Top level

The first figure is the top level design of FPGA architecture.

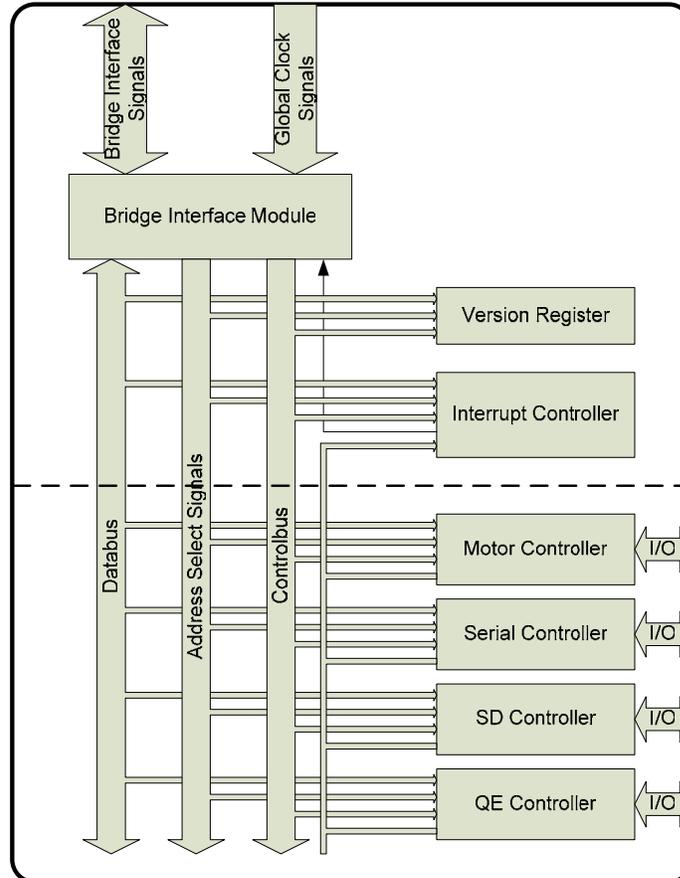


Figure 37 - FPGA Architecture

### Memory map en registers details

```
*****
* Mechatronic Simulation Setup
*****
```

```
Company:           University Of Twente
Engineer:          Mark Otto
Design Name:       Mechatronic Simulation Setup (MESS)
File Name:         Readme.txt
Project Name:      MESS Configuration 1
Description:
```

```
  Description of the configuration of the MESS Configuration 1.
  This file has three part.
  1 - Connectors description
  2 - Memory map
  3 - Register contents
```

```
Create Date:       04-10-2005
Last Modified:     04-10-2005
Revision:          v1.00
Revision 1.00     - Tested version
Revision 0.10     - Complete re-design
```

Revision 0.01 - Trial design

```
*****
* Connector description
*****
```

Connector(4I65/5I20):	1/2	3/3	4/4
Motor enable	Ena<1>	Ena<3>	Ena<5>
Motor direction	Dir<1>	Dir<3>	Dir<5>
Motor PWM	PWM<1>	PWM<3>	PWM<5>
Motor enable	Ena<2>	Ena<4>	Ena<6>
Motor direction	Dir<2>	Dir<4>	Dir<6>
Motor PWM	PWM<2>	PWM<4>	PWM<6>
Slave select (NC)	SS<1>	SS<2>	SS<3>
Serial clock (NC)	SCLK<1>	SCLK<2>	SCLK<3>
Serial out (NC)	SDOUT<1>	SDOUT<2>	SDOUT<3>
Serial in (NC)	SDIN<1>	SDIN<2>	SDIN<3>
Quadrature A	A<1>	A<3>	A<5>
Quadrature B	B<1>	B<3>	B<5>
Quadrature C	Idx<1>	Idx<3>	Idx<5>
Quadrature A	A<2>	A<4>	A<6>
Quadrature B	B<2>	B<4>	B<6>
Quadrature C	Idx<2>	Idx<4>	Idx<6>
Paper detected	PD<1>	PD<9>	PD<17>
Paper detected	PD<2>	PD<10>	PD<18>
Paper detected	PD<3>	PD<11>	PD<19>
Paper detected	PD<4>	PD<12>	PD<20>
Paper detected	PD<5>	PD<13>	PD<21>
Paper detected	PD<6>	PD<14>	PD<22>
Paper detected	PD<7>	PD<15>	PD<23>
Paper detected	PD<8>	PD<16>	PD<24>

```
*****
* Memory map
*****
```

The memory map is listed with the following details:

```
0x--      Offset from base address
r/w       Read or Write register
???      Description of register
```

All register use a 32 bit base address.

```
Version
0x00 - r - Version
```

```
IRQ Controller
0x10 - r/w - IRQ Latch
0x14 - r/w - IRQ Mask
0x18 - r/w - IRQ Missed
```

```
Motor Controller
0x20 - r/w - PWM Value
0x24 - r/w - PWM Value
0x28 - r/w - PWM Value
0x2C - r/w - PWM Value
0x30 - r/w - PWM Value
0x34 - r/w - PWM Value

0x40 - r/w - PWM Control register
0x44 - r/w - PWM Control register
0x48 - r/w - PWM Control register
0x4C - r/w - PWM Control register
0x50 - r/w - PWM Control register
0x54 - r/w - PWM Control register
```

0x60 - r/w - Motor configuration register  
 0x64 - r/w - IRQ Division

#### Quadrature Encoder Controller

0x70 - r - QE counter  
 0x74 - r - QE counter  
 0x78 - r - QE counter  
 0x7C - r - QE counter  
 0x80 - r - QE counter  
 0x84 - r - QE counter

0x90 - r/w - Counter control register  
 0x94 - r/w - Counter control register  
 0x98 - r/w - Counter control register  
 0x9C - r/w - Counter control register  
 0xA0 - r/w - Counter control register  
 0xA4 - r/w - Counter control register

0xB0 - r/w - QE control register

#### Paper Detector Controller

0xC0 - r - Paper detectors status

\*\*\*\*\*  
 \* Register contents \*  
 \*\*\*\*\*

#### Version

Version - Contains information about the current configuration.  
 Bit 31..24 - ProjectID  
 Bit 23..16 - DesignID  
 Bit 15..8 - Version  
 Bit 7..0 - SubVersion

#### IRQ Controller

##### IRQ Latch

This register contains the information about which IRQ generated the interrupt.  
 Writing a '1' to a bit resets the interrupt

##### IRQ Mask

This register can be used to enable interrupts

##### IRQ Missed

This register contains information on missed interrupt. This occurs when an IRQ re-occurs before the IRQ was reset. Writing a '1' to a bit resets the missed interrupt

#### Motor Controller

##### PWM Value

PWM Value is a signed 16 bit number which is output as 11 bit PWM plus sign on the direction bit.

Bit 15 - Direction bit  
 Bit 14..4 - PWM Value

##### PWM Control register

This register controls the PWM generator.

Bit 2 - Realtime PWM output bit status (read only)  
 Bit 1 - Interlace enable (interlaces PWM output for use as analog out)  
 Bit 0 - Enable -- enables PWM and ENA bit if set

##### Motor configuration register

This register controls all motors.

Bit 1 - Clear all PWM values (0 = NOP, 1 = Clear)

Bit 0 - Enable all Motors (0 = NOP, 1 = Enable)

#### IRQ Division

IRQ Division controls the rate of the interrupt generated by the Motor controller. The register is a 8 bit programmable divider for IRQ rate. This IRQ rate is defined by = PWM rate/IRQDIVSEL

#### Quadrature Encoder Controller

##### QE counter

This register returns the counter value of the quadrature encoder. This is a 32 bit position value.

##### Counter control register

This register controls the counter of the quadrature encoder

Bit 9 - Counter Mode (0 = quadrature, 1 = up/down)  
Bit 8 - Input Filter (0 = No filter, 1 = ~2 MHz input filter)  
Bit 7 - In bit (not used in this configuration)  
Bit 6 - Count enable (0 = disabled, 1 = enabled)  
Bit 5 - Clear On Index (0 = disabled, 1 = enabled)  
Bit 4 - Latch On index (0 = disabled, enabled)  
Bit 3 - Index Polarity (0 = active low, 1 = active high)  
Bit 2 - Real time index status (reads) counter clear (writes)  
Bit 1 - Real time input A status (read only)  
Bit 0 - Read time input B status (read only)

##### QE control register

This register controls all quadrature encoders.

Bit 1 - 0 = NOP 1 = Clear all counter  
Bit 0 - 0 = NOP 1 = Enable all counter

#### Paper Detector Controller

##### Paper detectors status

This register represents the status of the Paper detectors

Bit 23..0 - PD 24..1

## Appendix VII Experiments

This appendix contains all the details of the experiments that were performed to validate the MESS. The numbers of the input and output of the MScT start at zero. As a result the input and outputs in the models are numbered from zero up. For instance, the first quadrature encoder is called QE1 in the thesis, in the model design this is QE\_0.

Detailed information about 20-Sim experiment can be found on the CD of the project.

### Controller architecture

The top level control architecture is the same in all experiments. Figure 38 shows the model of the top level control architecture.

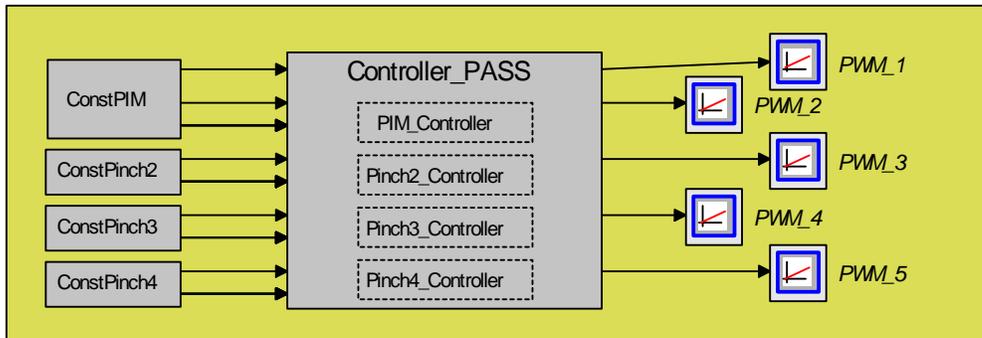


Figure 38 - Top level control architecture

The Controller\_PASS contains a controller for each PIM and Pinch. Figure 39 shows the content of the sub-model Controller\_PASS.

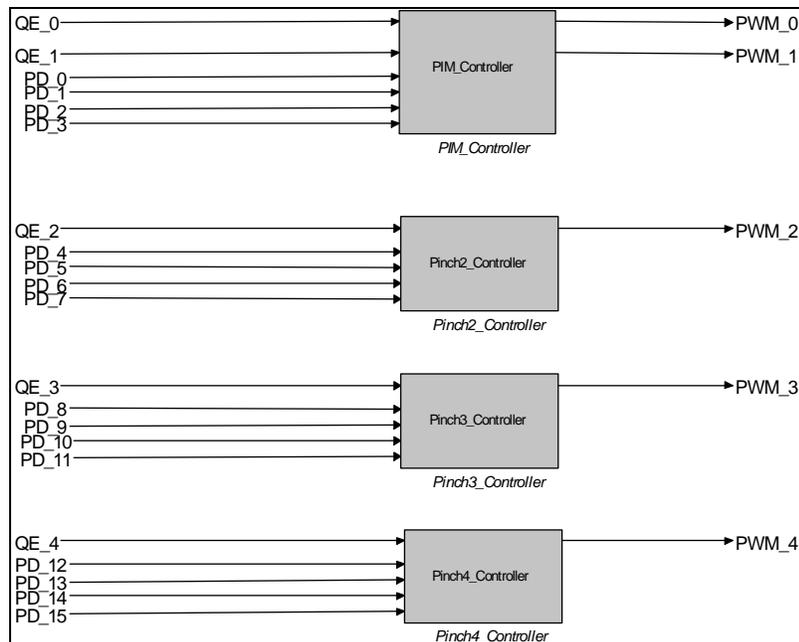


Figure 39 - Sub-model of Controller\_PASS

The implementation of the sub-models shown in Figure 39 will differ for each experiment.

### Unit experiments

This section contains the detailed of the unit experiments.

## Actuators and sensors

The experiments to validate the actuators and sensors use the same control architecture. Figure 40 shows the content of one of the Pinch\_Controllers. All motors have the same steering. The quadrature encoders (QE\_x) and sheet detectors (PD\_x) are only monitored. All motors have the same fixed PWM value and start with intervals of 1 second.

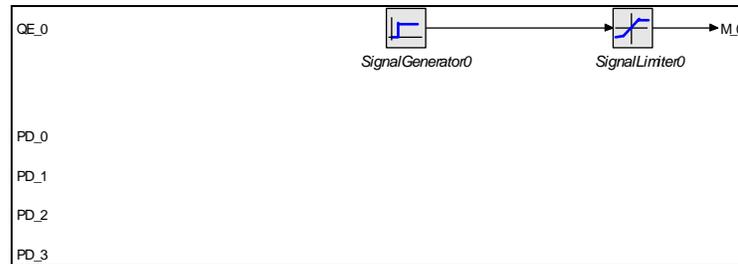


Figure 40 - Constant velocity steering

## Motors and quadrature encoders

Figure 41 shows the results of the motor and quadrature encoder experiment.

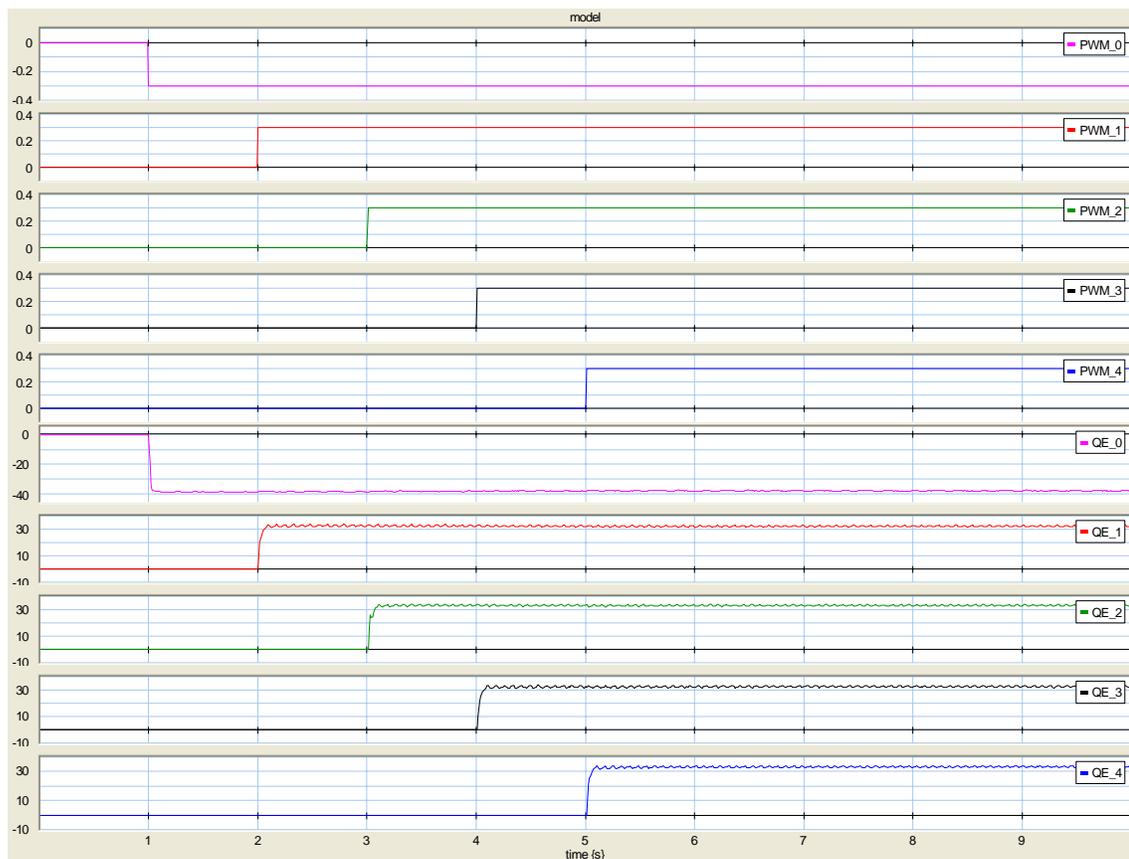


Figure 41 - Motor and quadrature plot

All motors and quadrature encoders work as predicted. The first roller of the PIM is placed on top of the paper sheets. The rollers of the other pinches are all placed on the bottom. Therefore the signal of the first motor is inverted.

## Sheet detectors

Figure 42 shows the result of the sheet detector experiment.

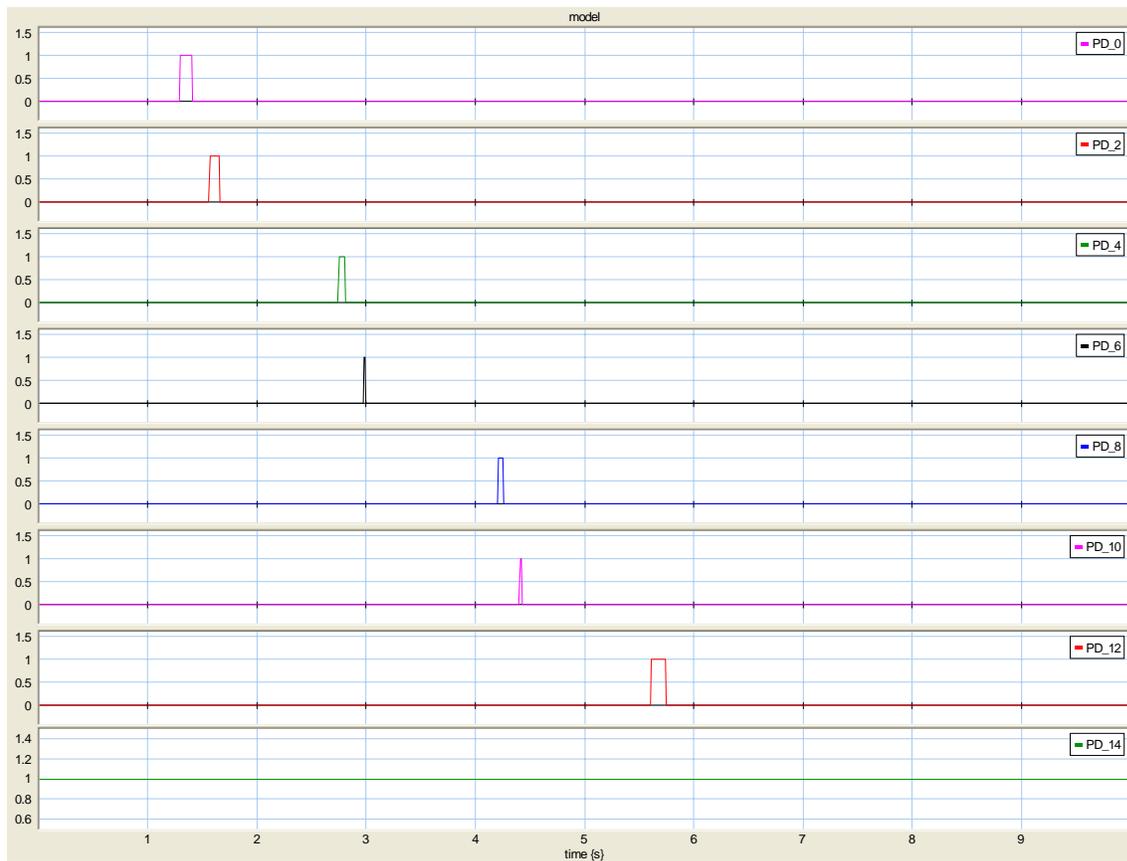


Figure 42 - Sheet detector plot

The last sheet detector is “stuck”. The mount of the top roller is too close to the sensor. The sensor detects the mount as a paper sheet.

### PIM

The experiments on the PIM test the performance of the PIM. The controller that is used is described in the section on the Single controller.

### Speed

Figure 43 shows the results of the speed experiment of the PIM. The experiment uses a single controller operating at 100 PPM with an inter sheet distance of 50 mm. The run-time of the experiment was set to 40 seconds and during 30 seconds the PIM produced 50 paper sheets.

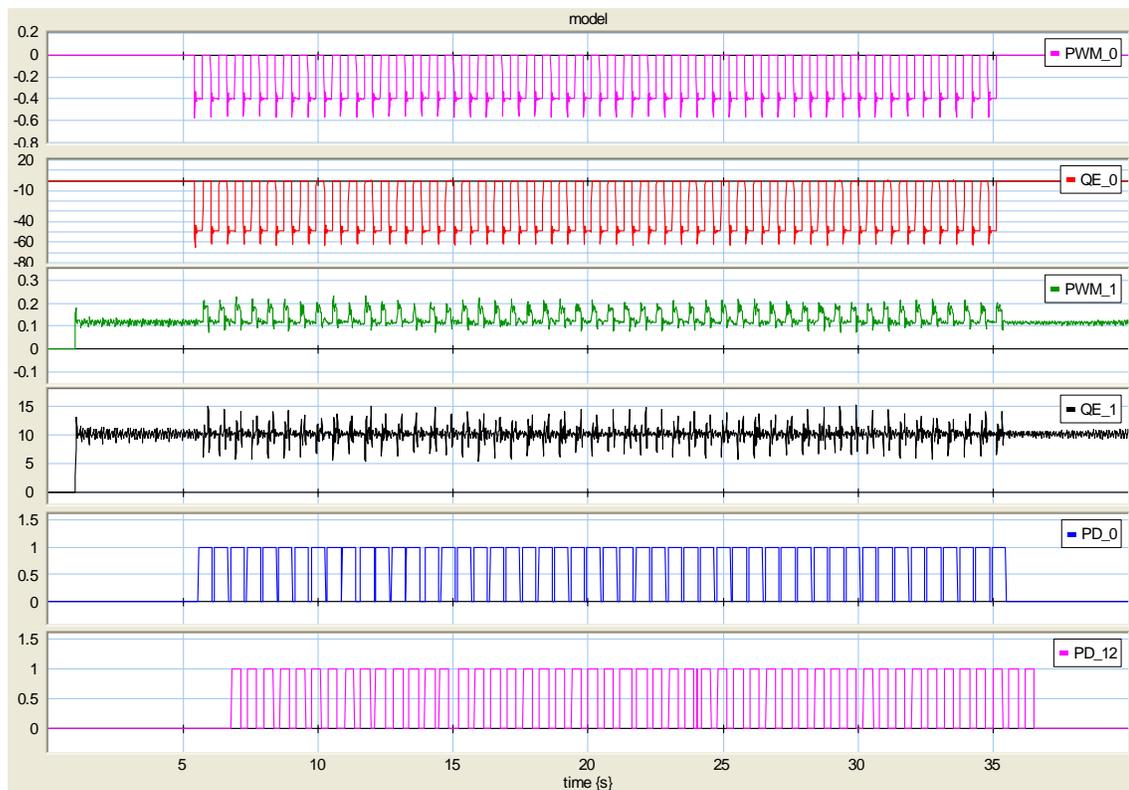


Figure 43 - PIM speed plot (100 PPM, 50 cm inter sheet distance)

The experiment was successful. The PIM is capable of speed up to 100 PPM.

### Multiple sheets

This experiment is performed to determine how often the PIM feeds more than one paper in the paperpath. Several experiments were performed. These experiments are:

- New paper without rubber layer, 100 PPM
- Used paper, 50 PPM
- Used paper, 100 PPM
- New paper, 50 PPM
- New paper, 100 PPM

Table 20 shows the results of the experiments.

Experiment	Sheet Count	Double sheets
Without rubber	59	9
Used, 50 PPM	54	4
Used, 100 PPM	55	5
New, 50 PPM	53	3
New, 100 PPM	52	2

Table 20 - Double paper sheets

The experiments without the rubber layer had an additional result. During this experiment a number of sheets entered the paperpath under a large angle (more than 5 degrees). A roller has two contact points on the paper. The angled input occurs when one of the contact points fails to grasp the paper sheet. Other experiments did not show these results. The additional friction of the rubber layer straightens the paper sheets.

### Inter sheet distance of paper

This experiment determines the deviation of the inter sheet distance produced by the pinch. The controllers of the PIM and pinches are set to a specific velocity which results in a certain inter sheet distance of paper. Six different experiments are performed. These setting of the experiments are:

- 10 mm inter sheet distance, 50 PPM
- 10 mm inter sheet distance, 100 PPM
- 30 mm inter sheet distance, 50 PPM
- 30 mm inter sheet distance, 100 PPM
- 50 mm inter sheet distance, 50 PPM
- 50 mm inter sheet distance, 100 PPM

Figure 44 shows the results of one of the experiments.

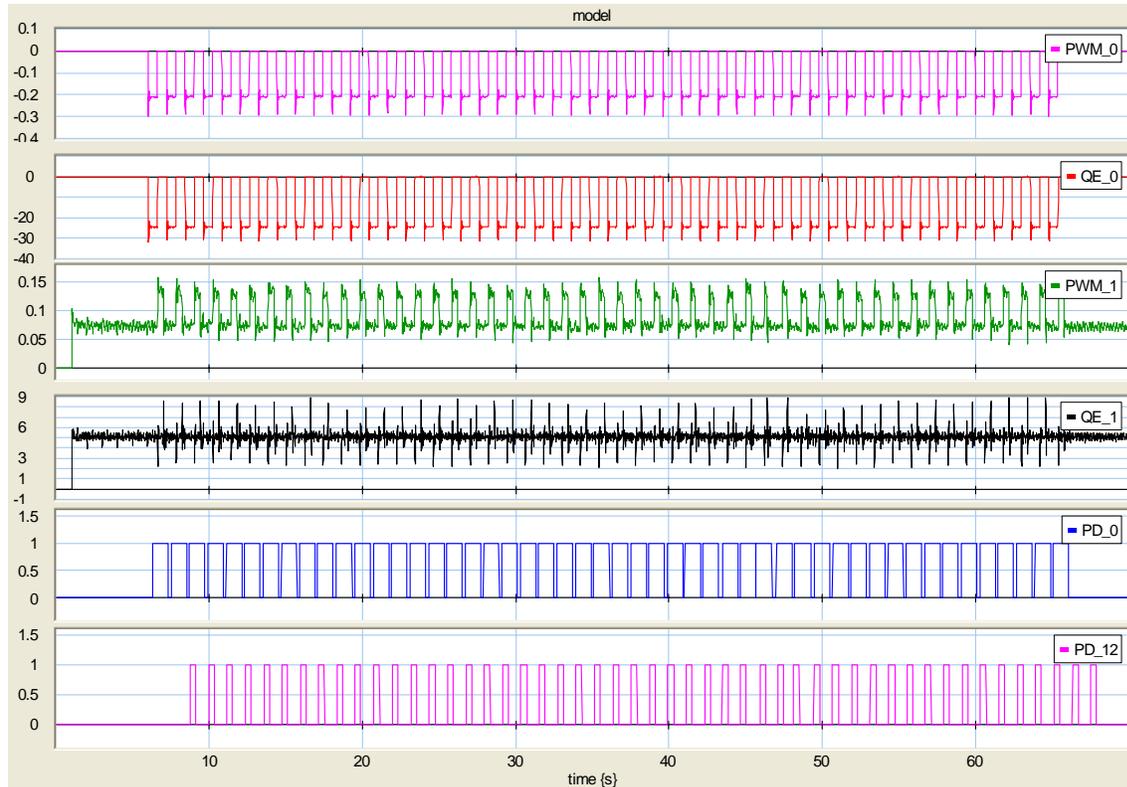


Figure 44 - Inter sheet distance plot (New, 50 PPM)

The deviation of the inter sheet distance was determined by calculating the front edges of the paper sheets when they enter the first pinch. The velocity of the first pinch is set higher than the velocity of the PIM roller. The PWM signal of the first pinch increases when a paper sheet enters the first pinch. The difference in quadrature pulses of two such events are used to determine the distance between the front edges of two succeeding sheets. Table 5 shows the results of the experiments. All experiments were performed one time.

Experiment	Maximum deviation	Standard deviation
New, 10 mm, 50 PPM	1,527	0,618
New, 10 mm, 100 PPM	2,913	0,938
New, 30 mm, 50 PPM	1,735	0,660
New, 30 mm, 100 PPM	3,576	1,434
New, 50 mm, 50 PPM	1,407	0,661
New, 50 mm, 100 PPM	3,213	0,678
Used, 50 mm, 50 PPM	1,695	0,864
Used, 50 mm, 100 PPM	3,734	1,343

Table 21 - Deviation of the inter sheet distance

## Integrated experiments

### Controller design

The Ziegler-Nicholas method was used to determine the value of the proportional controller. This method determines the proportional value with a rule of thumb. The proportional value is increased until the system starts oscillating. The proportional value and oscillating frequency is used to determine the parameters for a PID controller. The values for the PI and PID were also calculated but not used.

Ziegler-Nicholas					
P	$K_p = 0.5 * K_p \text{ grens}$				
PI	$K_p = 0.45 * K_p \text{ grens}$ $T_i = 0.8 * T \text{ grens}$				
PID	$K_p = 0.6 * K_p \text{ grens}$ $T_i = 0.5 * T \text{ grens}$ $T_d = 0.125 * T \text{ grens}$				
M0		P	PI	PID	
Kp grens	0,021	P	0,011	0,009	0,013
Tgrems	0,011	Ti		0,009	0,006
		Td			0,001
M1		P	PI	PID	
Kp grens	0,0200	P	0,010	0,009	0,012
Tgrems	0,013	Ti		0,010	0,007
		Td			0,002

The parameters for the first and the second motor are calculated. The proportional value of M1 is used for the other mothers. These motor are the same and drive the same type of part.

## Parameter calculations

Settings and fixed values		
Parameter	Value	Unit
Paper print length	210	mm
Inter sheet distance	50,0	mm
Pages per minute	100	ppm
Roller diameter	27,8	mm
Belt Gearing	2,056	
Extra Gearing	4,800	
Quadrature pulse count (pulses/rotation)	2000	

Calculations		
Parameter	Value	Unit
Paper velocity	0,433	m/s
Roller circumference	87,3	mm
Roller speed	4,962	rps
PIM motor velocity	48,955	rps
Pinch motor velocity	10,199	rps
PIM pulse gen omega	10,472	rad/s
PIM Quadrature pulse frequency	97,910	kHz
Pinch Quadrature pulse frequency	20,398	kHz
PIM displacement per pulse	4,425825	$\mu\text{m}$
Pinch displacement per pulse	21,24396	$\mu\text{m}$

Table 22 - Parameters calculations

The paper velocity is calculated with the paper length, the inter sheet distance and the number of pages per minute. The paper velocity is used to calculate the roller velocity. The roller velocity and gearings are used to calculate the motor velocities. The motor velocities and quadrature pulse count are used to calculate the quadrature encoder frequencies. The PIM pulse generator omega is calculated directly from the pages per minute. The displacement is calculated from the roller circumference and the gearings.

### Single controller

Results of the single controller are included in the main part of the thesis.

### Calibration

Detail on the calibrations are included the main part of the thesis.

### Pinches

Measurement errors deducted in the calibration section of the main part indicate a too slow measurement interval. The experiments on position the pinches need to be repeated. Detailed on the original experiments can be found on the CD of the project.

### Sheet detectors

Measurement errors deducted in the calibration section of the main part indicate a too slow measurement interval. The experiments on position the sheet detectors need to be repeated. Detailed on the original experiments can be found on the CD of the project.

## Literature

- 20-Sim (2005), *20 Sim*, <http://www.20sim.com/index.html>
- Buit, E. (2005), *PC104 stack mechatronic control platform*, M.Sc. Thesis, University of Twente, Enschede.
- Boderc (2005), *Beyond the Ordinary: Design of Embedded Real-time Control*, <http://www.esi.nl/site/>
- Groothuis, M. (2004), *Distributed HIL simulation for Boderc*, Masters Thesis, University of Twente, Enschede.
- Isermann, R., J. Schaffnit and S. Sinsel (1998), *Hardware-in-the-loop simulation for the design and testing of engine control systems*, Control Engineering Practice 7, (5), pp. 643-653.
- Mesa Electronics (2005), *MESA PC/104 PARALLEL AND MISC I/O CARDS*, <http://www.mesanet.com/>
- Suzuki, M. Isoda, M et al. (1998), *High Performance Rubber Rollers and Pads for Auto Sheet Feeders*, Hitachi Cable Review, U.D.C. 681.61.063.6 : [678.664 + 687.742].
- Xilinx (2004), Xilinx ISE Webpack & Modelsim XE, <http://www.xilinx.com>