Graduation Report UCM integration

UNIVERSAL CAPACITY MEASUREMENT SYSTEM INTEGRATION & IMPROVEMENT

The results of the Qualification of the UCM using a Piezo Driven Stage & fixed Capacitors in Electrical and Mechanical Terms and the Results of a Redesigned UCM in the Same Terms

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PREFACE

Almost each Bachelor study ends with a graduate internship program. This program usually takes place in the final semester and forces the student to show all his skills in a new environment, usually a company. During 90 days, the student has to put all his knowledge to the test in order to work out an assignment provided by the internship company.

The goal of the student is to show his teachers and his internship environment, that he is capable of using everything he has learned in practice. Both the student and the internship environment benefit from a successful partnership: the student gets a good rating and the company gets new knowledge, products or anything else advantageous.

The company Janssen Precision Engineering (JPE) is an environment where you will be severely tested on your skills and properly guided along the way. JPE consists of a group of engineers, under the leading supervision of Huub Janssen, who together create and develop high-tech machinery. A mixed know-how of mechanical and electrical skills is present making it possible to design new products with knowledge of every design aspect.

During my internship here I was confronted with both electrical and mechanical design constraints and an understanding of the interaction between both was needed to solve underlying relations. The project I had been working on involved a stage, which was able to move in six degrees of freedom over a length of tens of micrometers. The weakest part of the stage was the electronics created to read out six capacitive sensors inside the stage. My main task was to replace these electronics with a new capacitive measurement system, the UCM, and to qualify the UCM using the stage. Qualifying the stage led to conclusions which were used to plan the continuing activities of my internship.
The final activity which I enjoyed the most was the creation and testing of a redesigned UCM (UCM+).

This report with all my results has been made possible with the great support of all the colleagues at JPE, who always had time to answer any silly questions. Special thanks go out to my tutor Bart van Bree and Huub Janssen, who never gave up on me. I would also like to thank all the electrical engineers, for their technical support and criticism on my electronic designs; without it, my design would have gone up in smoke.
Of course, none of my achievements at JPE would have been possible without the time and energy of all the Hogeschool Zuyd teachers. Many thanks to Pierre Wielders, who unfortunately is no longer with us, but he always used to keep me focused and always kept the education level high, which will ultimately only benefit all his students.
A word of thanks also goes out to Leon Muijtjens, for his continuous support and interest in my internship here and in other activities.

I hope that all information in this report is clear and joy can be found in reading it.

Floris Grommen

CONTENTS

FIGURE LIST

RELEVANT DOCUMENTATION

Ref	Title, author	File name	Date
[1]	UCM Integration, Floris Grommen	UCMi_Floris.doc	2008-01-31
[2]	Investigation Report Piezo Driven Stage, Bart van Bree	PDS_investigation.doc	2004-03-29
[3]	Piezo control system for piezo driven stage, Rudolf Geurink	PCS_PDS_01_invest.doc	2004-03-05
[4]	Test report VeePac Stage	Test_V06-05.doc	2006-03-23
[5]	Memo VeePAC stage test procedures, Rudolf Geurink/Ronald Smeets	VPAC_Test_Proc.doc	2007-01-12
[6]	Comparison between old log with UTI and new log from controller with UCM 25-3-2009, Floris Grommen	Disp_test_results_25-3-2009_UTI_vs_UCM.html	2009-03-25
[7]	Universal Capacity Measurement, Laurens Swaans	UCM_GR.doc	2005-11-01
[8]	xPC Target Quick Reference Guide for v2.5 (R14.0), F. Gonzalez	xpc_quick_reference_v2.5_t1.pdf	2004-09-03
[9]	VEEPAC SOFTWARE V5.0, Rudolf Geurink	VPAC_N_50.doc	2006-10-11
[10]	BWT-TP POSITION SENSORS, Roel Metz	TR_BWT-TP_Position_Sensors.pdf	2008-11-10
[11]	Capacitor, Wikipedia	http://en.wikipedia.org/wiki/Capacitive	2009-06-06
[12]	D-510 PISeca™ Capacitive Sensors, Physik Instruments	D510_Datasheet.pdf (www.pi.ws)	2008
[13]	E-852 PISeca™ Signal Conditioner, Physik Instruments	E852_Datasheet.pdf (www.pi.ws)	2008
[14]	MS3110 Universal Capacity Readout™ IC, Irvine Sensors	MS3110_Datasheet_Use.pdf	2005-04-01
[15]	ADS1255 ADS156, Texas Instruments	ADS1255.pdf	2008-09-01

DOCUMENT HISTORY

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DEFINITIONS

Definition	Description
Dynamic range	Highest detectable signal divided by smallest detectable signal

ABBREVIATIONS

Abbreviation	Description
PCS	Piezo Controlled Stage
UCM	Universal Capacity Measurement prototype, reference to UCM prototype, rev. UCM_E_01_0011a
UCM+	Universal Capacity Measurement redesign, reference to UCM redesign, rev. UCM_E_01_002
UTI	Universal Transducer Interface, used to refer to first measurement system used in PCS
PCB	Printed circuit board
(A)IOS	(Automatic) input-output shaping. Algorithm used with MS3110 to focus on input when static.

1 SUMMARY

This document contains development and test information regarding further development of the Universal Capacity Measurement (UCM) system. The UCM is a printed circuit board (PCB) designed to measure capacitance in the 0-10pF range with great accuracy. The UCM will typically be used to work with two electrode capacitive sensors, which usually have a capacity in this range.

A prototype UCM is already built and placed 6 times in one case. This case can be connected to the piezo driven stage developed by JPE. This stage is capable of moving in 6 degrees of freedom with the use of 6 piezo actuators. Six capacitive plate sensors are placed inside this stage to measure its current position. The UCM was designed to replace the first capacitive measurement system in the piezo stage (UTI). Replacement of this UTI measurement system showed that the UCM was superior in bandwidth and accuracy. The resolution was increased approximately 4 times using the UCM with a 25 times wider band width.

To better examine the limits of the UCM, more tests were conducted with shielded fixed capacitors, but with the same UCM settings as with the stage connected. These tests were needed to verify if the new piezo driven stage setup was still limited by its capacitive measurement system or one of the other components. Tests showed similar noise levels with the fixed capacitors or stage connected, so it can be concluded that the UCM still is the limiting factor in the piezo driven stage.
These tests with fixed capacitors also showed a great variance in the performance of different UCM's. A short investigation showed that these differences were mostly caused by the use of an untrimmed input chip, the MS3110. This chip is responsible for converting the input capacity in an analogue voltage with a known relation. The worst UCM performances were caused by a 25 pins sub-d connector, which connected the inputs of the UCM to the capacitive sensors. Crosstalk occurred here, especially for UCM's which had an almost similar excitation frequency. Adjusting this frequency greatly attenuated the differences between the UCM's. The best UCM had a resolution around 480aF (C=3.3pF) with a sample frequency of 2Khz.

Some time was also spent in investigating the best sensor position which provided the best mechanical resolution. UCM test results and some math showed that measuring high capacities, or low gap widths, gives a much better mechanical resolution than measuring low capacities. In fact, only trimming all the sensors to the same optimal gap width could have a theoretical mechanical resolution improvement of almost two.

The tests done provided some recommendations for creating a more accurate piezo stage. The recommendation which was expected to have the most improvements and had to be done anyway, was the redesign of the UCM. The build-up redesign is a better, compacter and cheaper version of the original UCM, the redesigned UCM (UCM+). Noise levels were around 80% of the UCM.

Examining the UCM+ more, especially the MS3110 input chip, created the idea of input-output shaping (IOS). This way, the sensitivity of the output of the MS3110 was adjusted depending on input changes in order to attempt to obtain a higher resolution. The idea is the input of the MS3110 does not have to cover the full 10pF range, but only a portion around the current value. By reprogramming it with a new offset and gain, higher resolution was obtained. Lowering the input range from 10pF to 1pF increased the resolution almost 3 times; lowering it again from 1pF to 0.1pF increased the resolution another two times. The only problem is the error in each offset and gain setting, which causes the output to make jumps in absolute capacity. A solution to this problem could be a calibration routine which creates a table with error correction factors for each register setting to erase any jumps that might occur in the output.

The last tests done were to fulfill a popular request. Everybody was curious how the UCM+ performed compared to other capacitive measurement systems, for example Physik Instrumente (PI). PI develops capacitive sensors and measurement electronics which are able of obtaining nanometer resolutions. An old test done at JPE with a PI sensor and electronics was compared to tests with the UCM+ using similar sensor input settings. Comparing both tests showed that the UCM+ can compete with PI's products, especially when using the IOS technique. In the 10pF range setting, the UCM+ showed less noise up to a sample frequency of 160Hz. The 1pF range shows the noise of the PI data almost cut in half; the 0.1pF setting reduces the PI's noise by a factor three.

With all the test results, it was also possible to formulate recommendations to create capacitive sensor with optimal mechanical performance. Usually at JPE, a needed stroke and resolution are known and a sensor has to be found which can match these specifications. The dimensions for a capacitive sensor can be calculated by assuming optimal conditions for the UCM+. The UCM+ performs best when an optimal capacitive input range (5-10pF) is used. An Excel worksheet is available which calculates optimal sensor settings with certain known specifications. The needed capacitive resolution is also visible.

2 INTRODUCTION

This document describes the new developments and test results of a Universal Capacitive Measurement (UCM) system. This system has been developed 5 years ago by JPE to measure capacities in the 0-10pF range with great accuracy. An UCM prototype has been built already and roughly qualified. However the UCM was originally designed to be implemented in a 6 degrees of freedom stage which houses 6 capacitive sensors. The UCM still has to be incorporated in this stage with its controller and tested properly.

The first assignment is to integrate the UCM in the stage and to compare test results with the UCM to test results with the old measurement system. It is important to think how both measurement systems will be qualified in order to make a fair comparison. Reference LVDT sensors are mounted on the stage to verify its movement, but it is questionable whether their 60nm resolution will be sufficient to accurately measure the movements of the stage with an improved measurement system. Test results of the UCM will be further analyzed with the use of fixed capacitors instead of capacitive sensors, to make a more accurate comparison of the pure UCM results versus the total results when the stage with controller, piezo actuators and UCM is used. With all these test results, recommendations can be made regarding the continuing development of the stage and UCM. If the time allows it, one or more of these recommendations will also be carried out.

This report contains 7 main chapters. Chapters are divided chronically more or less, but all test results from the UCM prototype and redesigned UCM have been placed in two separate chapters. The first chapter contains some background information about JPE itself, about the UCM and stage background followed by a short description of the basics of capacitive measurements. The next chapter expands over the hardware and software changes in the stage controller and contains a list of the expected results of the stage's performance using the old and new measurement system.
Chapter 5 contains a list of all the tests done with the stage and the UCM prototype. The last test is a mathematical analysis of the calibration setting of the capacitive sensors in the stage. The conclusion of the tests in chapter 5 was the recommendation of a redesigned UCM. The investigation report prior to the design and the realized design can be found in chapters 6 and 7. Chapter 8 contains tests with their results again, only now from the redesigned UCM. One test here compares the UCM+ to another capacitive measurement system from PI.
The last chapter contains the most important conclusions from this report with some recommendations on how to improve the UCM's and stage's performance. All the tests from this report allowed me to create some equations which can calculate an optimal capacitive sensor using a few mechanical specifications.

3 BACKGROUND

This chapter provides some background information regarding the UCM and its use. Since the UCM has already been build, tested and roughly qualified, an introduction is needed before more details will be discussed. A short company profile is listed first however.

3.1 Company profile

Janssen Precision Engineering consists of a group of engineers that develop and assist in the development of high-tech machinery and equipment. They have a wide field of operation which include the semiconductor industry, space projects, medical equipment and astronomy. Although most engineers working at JPE have a mechanical background, there are also several electrical engineers present and JPE is trying to profile itself more and more as a mechatronics company, where both skills are well present. By combining both skills; JPE can have a complete understanding of their developed products and assist their customers with great know-how, especially in the development of real time closed loop systems. These kinds of systems demand great knowledge in the mechanical and electrical field in order to get the performance needed.

One example of a product developed by JPE used in controlled closed loop system is a stage with nanometer resolution and tens of micrometers stroke in 6 degrees of freedom. Figure 3.1 shows a picture of this stage. The floor can be manoeuvred in all linear directions (x, y and z) and rotated around all its axes (Rx, Ry, and Rz). These movements are possible with the V-shaped actuators designed by JPE. These actuators are called VeePAC's, V-shaped precision actuators.

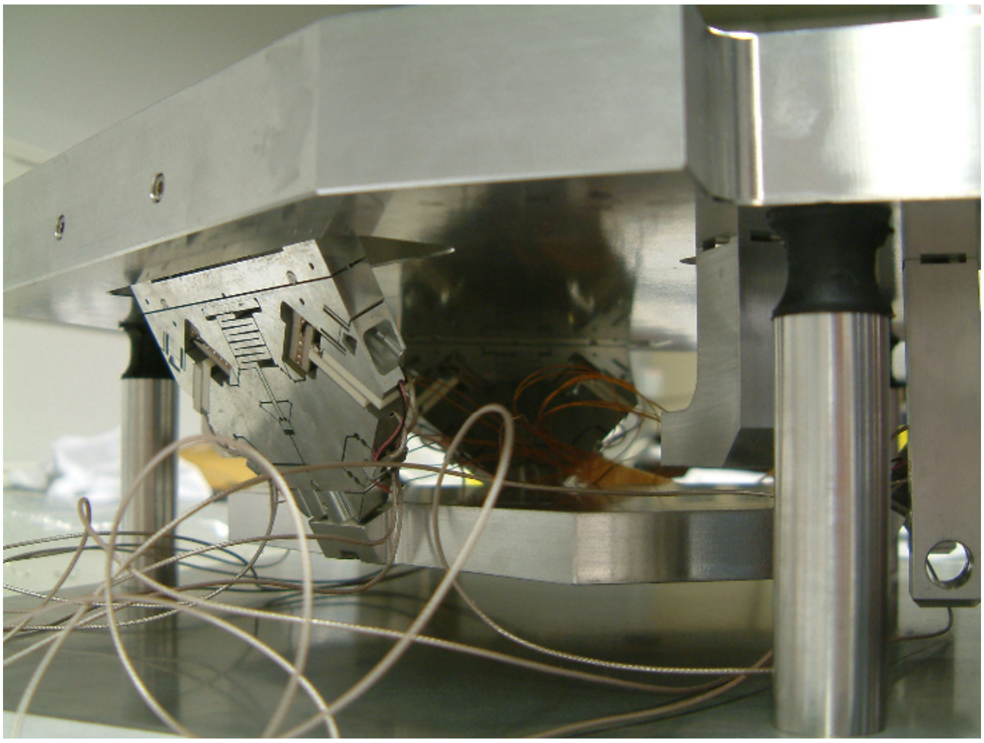
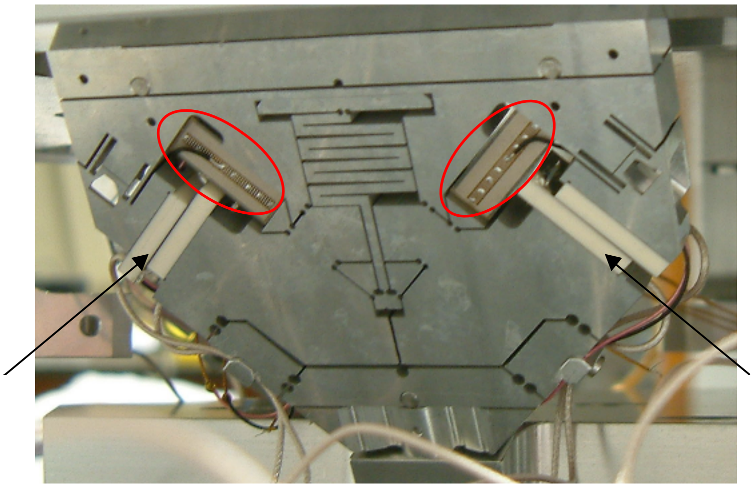


Figure 3.1 6 degrees of freedom stage with VeePAC modules

3.2 VeePAC

The mentioned VeePAC's are equipped with piezo actuators. By applying a voltage to these piezo actuators they expand. When a voltage of 150V is applied to them they expand 18µm. The piezo actuators are located in Figure 3.2 in the red circles. The VeePAC module can move in pure x and z direction. Stiffness of the construction prevents movement in other directions. One module can move on pure x-axe when a voltage is applied to one of the piezos. When both of them are powered the module expands on the z direction. In order to create a 6 degrees of freedom stage, 3 of these VeePAC modules are connected to one mass, each module at a 120˚ angle from each other.
The piezos are driven by a very accurate power supply, which should be able to drive the piezos with a nanometer accuary.



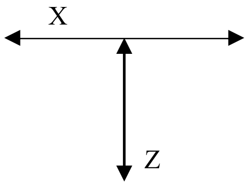


Figure 3.2 Close-up of VeePAC module with piëzos circled

Piëzos however are very liable to drift and hysteresis so the voltage applied to them does not always mean that the piëzos expand the same length. Especially when a nanometre resolution is required another measurement system is needed to check stage position. Also temperature variations of the VeePAC module can alter a predicted movement.

JPE choose to use capacitive sensors since they are vacuum compatible and can be read with a nanometer resolution. In Figure 3.2 the capacitive sensors are marked with the arrows. Two plates are placed close to each other. The capacitance of the plates is an inverse value for the gap displacement, provided that the place surface is much larger than the gap between the plates.

JPE has already developed a fully functional 6 DoF (degrees of freedom) stage with all the needed electronics. One Piezo Controlled stage (PCS) consists of:
- One stage with 3 VeePAC modules
- One piezo power supply
- Measurement electronics to read out the capacitance of the 6 plate capacitors
- One controller which controls the piezos and reads out the sensors

The current measurement system is the of-the-shelf Universal Transducer Interface (UTI), developed by a company called Smartec. The two biggest disadvantages of this measurement are the small bandwidth (8 Hz) and a resolution of only 13 bits. The total system specification is limited by these values so improving the measurement system improves total system performance.

A new measurement system has also already been developed by JPE. It is called the Universal Capacity Measurement (UCM) system. It is built around an IC which is able to convert a capacity in a voltage with a higher resolution and at a much higher sample frequency. [1] Contains test reports of the UCM tested with fixed capacitors.

One UCM printed circuit board (PCB) can read out one sensor. A case has already been built with 6 UCM's inside and all connectors needed to upgrade the current UTI case with the UCM case. Functional software is present on the UCM's, only the main controller, running on a PC/104 system, has to be updated in order to communicate with the new UCM measurement system.

The goal is to test the UCM's performance in a real time controller and to verify the previous results obtained with static measurements. With these results the UCM can be analyzed further to verify if more improvements are possible and if the created specifications are feasible.

3.3 Capacitive measurements background

It is important to have some knowledge about how capacitive measurements are done and the difficulty in qualifying a capacitive measurement system properly. Especially since most applications are not interested in the capacity of the sensor, but in the gap width between the sensor plates.

Figure 3.3 shows a basic plate capacitor. By charging one plate, an electric field is created between both plates. The electric field will be uniform around the center of the plates as long as the plate area A is much greater than the gap between the plates, d. If this is true the following relation exists between capacitance and d:

$$C[F] = \frac{\varepsilon[\frac{F}{m}]A[m^2]}{d[m]}$$

Equation 3.1 Conversion from C to d

Units are shown in parentheses. ε Is the dielectric constant, which is defined as $\varepsilon_R\varepsilon_0$, the relative permittivity of the dielectric multiplied by the permittivity of free space.

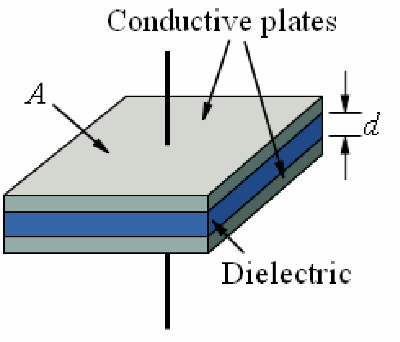


Figure 3.3 Basic plate capacitor [11]

Figure 3.4 shows a graph with 2 logarithmic axes where the capacity is plotted versus the sensor gap width. Since the relation between the two is almost a straight logarithmic line, the relation in noise between the two will probably have a similar relation, assuming the capacitive noise is fairly independent of the input capacitance. The chip used to convert capacitance into a voltage in the UCM has a specified noise output of $4aF/\sqrt{Hz}$. So the noise created by this chip will be fairly constant. With this knowledge and Figure 3.4, it can be seen that a fixed deviation in capacity will always have an increasing deviation in micrometers for decreasing capacities. In the graph, a 1pF deviation is assumed, next to it are the deviations expressed in micrometers. The non-linear relation between the noises is one of the reasons why a deviation in gap width should at least include the measured capacity, in order to provide some comparable test data.

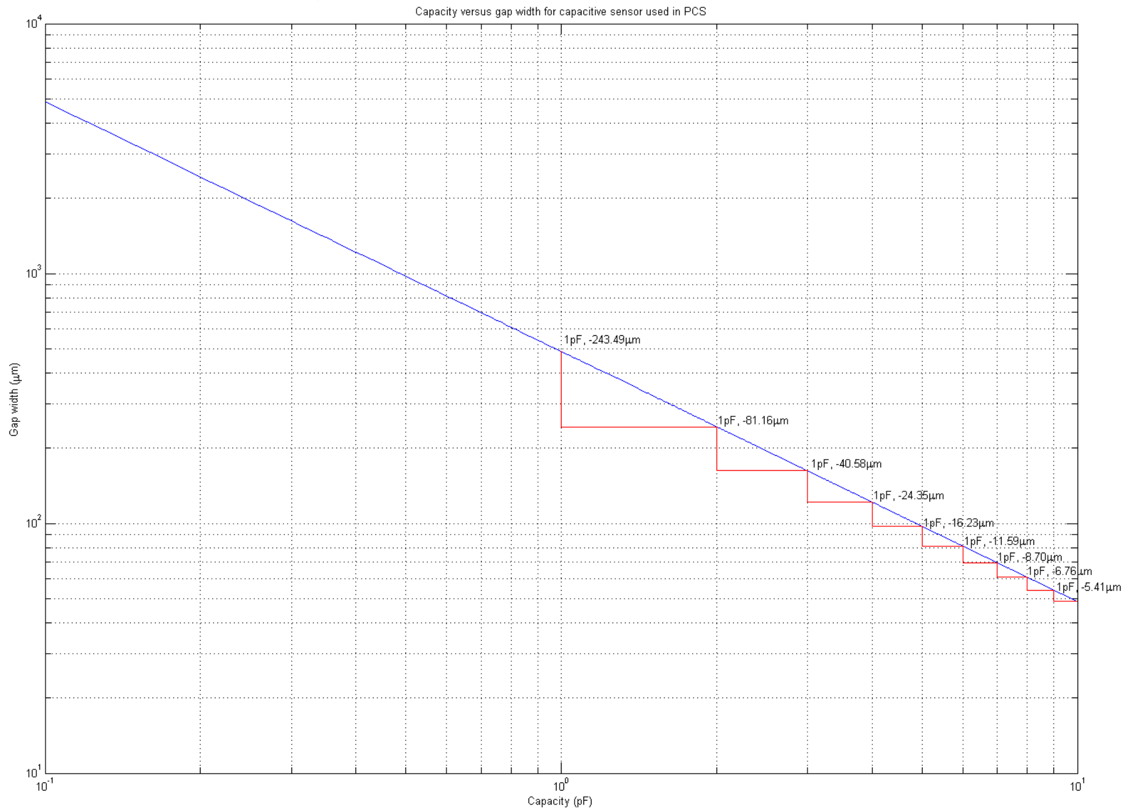


Figure 3.4 Graph showing logarithmic relation between capacity and gap width from PCS capacitive sensors

4 PCS UPGRADE INVESTIGATION

The first step is integrating the UCM in the piezo controlled stage. The investigation in this chapter focuses on qualifying the UCM in a real-time controller used to control the Piezo Controlled Stage (PCS). The UCM will replace the UTI which is responsible for reading out the capacitive sensors. The UCM is designed to have a superior resolution and bandwidth compared to the UTI. In order to increase the bandwidth also, the communication between the capacity readout module and PC/104 controller has to be modified also.

4.1 System specification

4.1.1 Current system specifications which are confirmed by test results using UTI

The current system specifications regarding resolution, stability and repeatability for the JPE piezo driven stage can be found in [4]. These specifications and other specs are summarized in Table 4.1 through Table 4.4. Figure 4.1 shows the schematic layout of the current system. Currently the user interface is able to receive controller information. Set points can only be set by connecting the keyboard mule of the PC/104 to the RS232 input of the user interface.

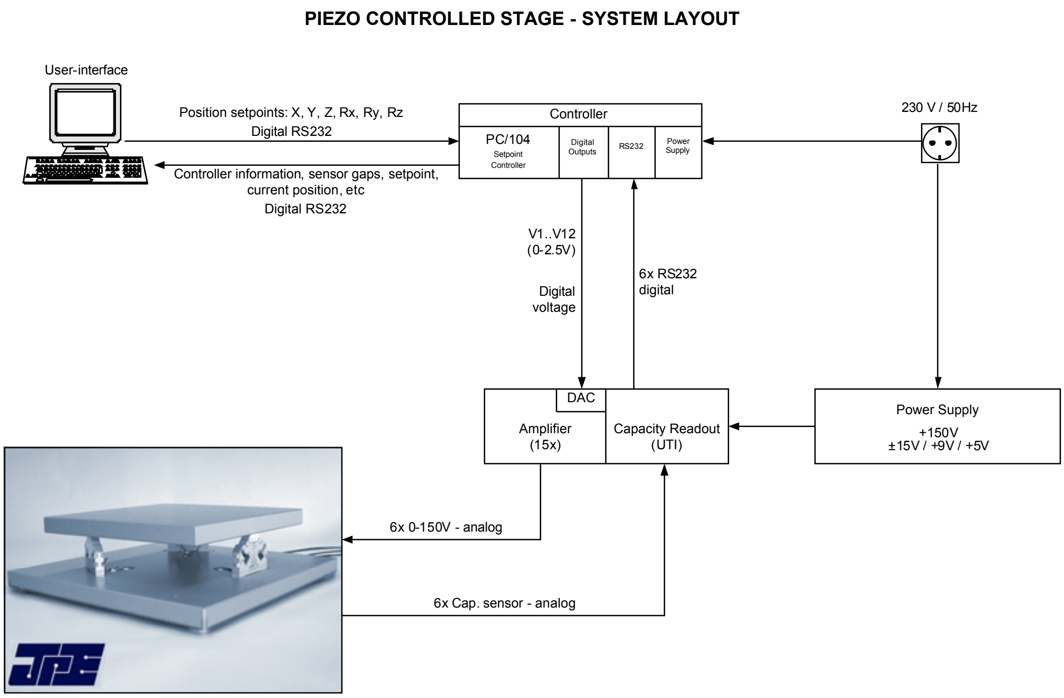


Figure 4.1 Schematic system overview with UTI

Table 4.1 Complete system specifications with UTI

	Setpoint	Cap sensor	Cap sensor	Controller	Control voltage	Drive voltage
Axes	6	6	6	6	6	6
Type	Digital	Analogue	Digital	Digital	Digital	Analogue
From	User interface	Sensor plates	Capacity readout (UTI)	Setpoint calculations	Controller	DAC/Amplifier
To	Controller	Cap. measurement electronics (UTI)	Controller		DAC/Amplifier	Piezos in stage
Speed	5Hz	10Hz	10Hz	75Hz	75Hz	75Hz
Dynamic range	10^6	10^4	10^4	10^6	10^5	10^5
Resolution	20 bits	14 bits	14 bits	20 bits	18 bits	18 bits
Data flow per axis			10 kb/s		2 kb/s	

Table 4.2 shows stroke verification in global coordinates. A ±10% variation can occur due to spread on the stroke of piezo-actuators. A ±5% variation can occur due to machining and mounting tolerances.

Table 4.2 Stroke criteria of the table in global coordinates

DOF	- Stroke	+ Stroke	Tolerance
x	-76 µm	76 µm	±15%
y	-68 µm	68 µm	±15%
z	-88 µm	88 µm	±15%
Rx	-1000 µrad	1000 µrad	±15%
Ry	-1200 µrad	1200 µrad	±15%
Rz	-900 µrad	900 µrad	±15%

Table 4.3 shows stability criteria in global coordinates. Stability check by monitoring the table position in global coordinates over an 1 hour period and a maximum temperature fluctuation of ±0.1 ºC.

Table 4.3 Stability criteria for the table in global coordinates

DOF	RMS stability @ dT < ±0.1 ºC
x	0.150 µm
y	0.150 µm
z	0.300 µm
Rx	5 µrad
Ry	5 µrad
Rz	5 µrad

Table 4.4 shows resolution of the table position in global coordinates. The resolution is verified by making increasing steps in batches of 10 identical steps. Resolution is declared to be equal to the smallest step size for which these steps become distinguishable individually.

Table 4.4 Resolution criteria for the table

DOF	Resolution	Steps made
x	0.100 µm	10x0.05 µm, 10x0.100 µm, 10x0.250 µm
y	0.100 µm	10x0.05 µm, 10x0.100 µm, 10x0.250 µm
z	0.100 µm	10x0.05 µm, 10x0.100 µm, 10x0.250 µm
Rx	5 µrad	10x2 µrad, 10x4 µrad, 10x10 µrad
Ry	5 µrad	10x2 µrad, 10x4 µrad, 10x10 µrad
Rz	5 µrad	10x2 µrad, 10x4 µrad, 10x10 µrad

Test criteria are verified with 6 LVDT probes mounted in the stage with a theoretical resolution of 60nm and 0.5µrad. Resolution is a little improved by averaging measurement data, but the probes are mainly used for verification of the movements of the table. More accurate position info can be obtained by logging the controller data which gives out the coordinates calculated by the UTI itself as well as position information.

4.1.2 Target system specifications replacing UTI with UCM

The UCM has already been tested separately [1]. Results obtained here should be translated to new system specifications for the PCS. The schematic of the new total system layout can be seen in Figure 4.2.
Table 4.6 shows the UCM demands which were proved to be possible [1]. The demand for resolution also has been translated to the gap width of the capacitive sensor for a measured value of 5.6 pF. Conversion assumes a plate size of 55 mm^2 for capacitive sensors. Table 4.7 and Table 4.8 show these values translated to mechanical specifications. Stroke remains unchanged.

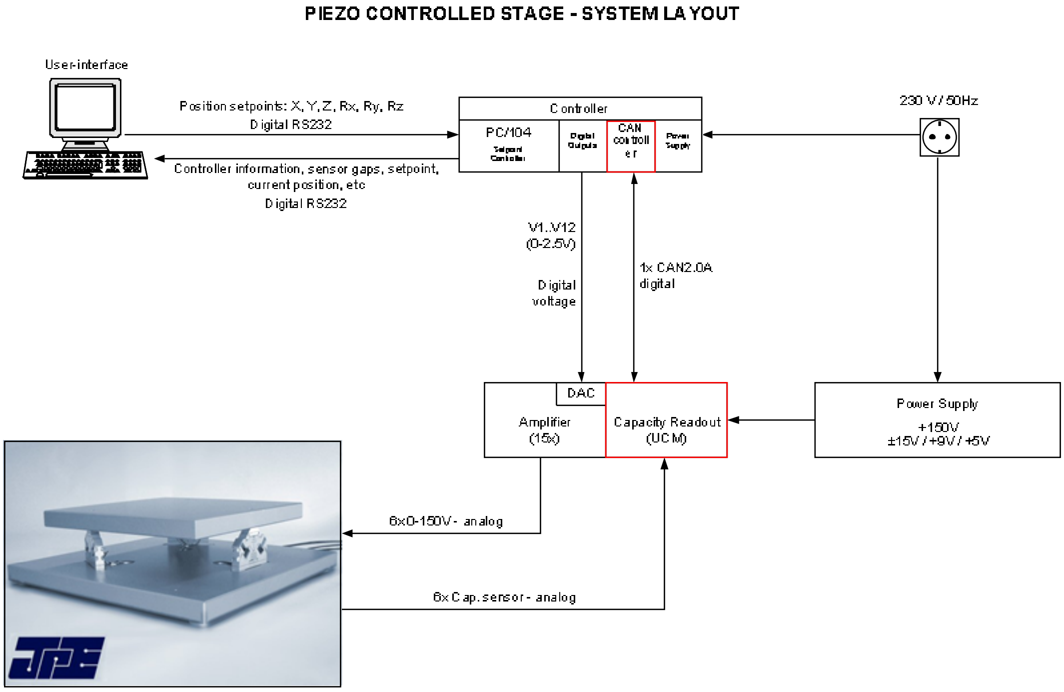


Figure 4.2 New schematic system overview with UCM, modifications in red

Table 4.5 Complete system specifications with UCM

	Setpoint	Cap sensor	Cap sensor	Controller	Control voltage	Drive voltage
Axes	6	6	6	6	6	6
Type	Digital	Analogue	Digital	Digital	Digital	Analogue
From	User interface	Sensor plates	Capacity readout (UCM)	Setpoint calculations	Controller	DAC/Amplifier
To	Controller	Capacity readout (UCM)	Controller		DAC/Amplifier	Piezos in stage
Speed	5Hz	500Hz	500Hz	100Hz	100Hz	100Hz
Dynamic range	10^6	10^5	10^5	10^6	10^5	10^5
Resolution	20 bits	16 bits	16 bits	20 bits	18 bits	18 bits
Data flow per axis			37,5 kb/s		10 kb/s	

Table 4.6 UCM specifications

Test point (short term; long term)	Demand
Stability fixed capacitor UCM input (1min; 1hr)	300 aF; 600 aF (3σ)
Converted to gap width for C_{IN} = 5.6 pF (1min;1hr)	5.0 nm; 10 nm (3σ)

Table 4.7 shows stability criteria in global coordinates. Stability check by monitoring the table position in global coordinates over an 1 hour period and a maximum temperature fluctuation of ±0.1 °C.

Table 4.7 Stability criteria for the table in global coordinates

DOF	RMS stability @ dT < ±0.1 °C (1 hr)
x	10nm
y	10nm
z	10nm
Rx	100nrad
Ry	100nrad
Rz	100nrad

Table 4.8 shows resolution of the table position in global coordinates. The resolution is verified by making increasing sized steps in batches of 10 identical steps. Resolution is declared to be equal to the smallest step size for which these steps become distinguishable individually.

Table 4.8 Resolution criteria for the table

DOF	Resolution	Steps made
x	5nm	10x1nm, 10x5nm, 10x10nm
y	5nm	10x1nm, 10x5nm, 10x10nm
z	5nm	10x1nm, 10x5nm, 10x10nm
Rx	50nrad	10x10nrad, 10x20nrad, 10x50nrad
Ry	50nrad	10x10nrad, 10x20nrad, 10x50nrad
Rz	50nrad	10x10nrad, 10x20nrad, 10x50nrad

Test criteria are no longer verified with the 6 LVDT probes, since their resolution is too limited to accurately measure the performance of the stage with the UCM implemented. The position info is now only obtained by logging the controller data which gives out the coordinates calculated by the UCM itself as well as position information.

4.2 Upgrade design considerations

The current system will be modified in its hardware and software. Ultimately, both parts will have to be optimized so the UCM can show its best performance as well as the PCS. The first step however, will be to replace all the UTI parts with the UCM and to run some tests and compare the test results with an old test run from the PCS with the UTI used as measurement system. The new parts are encircled in red in Figure 4.2.

4.2.1 Hardware modifications

The UCM communicates over a CAN bus. The current PC/104 controller will therefore be upgraded with a CAN extension board. Since the whole controller is programmed in MATLAB xPC, a board is selected which already has drivers implemented in the xPC library. Only Softing produces CAN boards which are supported; leading to the purchase of the single CAN channel board CAN-AC1-104 through the company Raster Products.
It is compliant with CAN 2.0A as well as B, but only A, 11-bit identifiers, will be used. The baud rate to be used is 1MBd.
The UTI system which communicates using RS232 with a RS232 extension board will be disconnected. The Diamond Emerald MM 4 channel RS232 can be removed from the PC/104, only the logging which is also sent using one RS232 channel will have to be rerouted to a COM channel on the PC/104 main board itself.
The UCM also requires 2 digital lines to reset all the master and slave microcontrollers at the same time. The PC/104 already has an expansion board with 48 digital I/O lines, only most of these lines are used to drive a DAC board which signals the piezo amplifiers. There are only lines available which would be just enough to reset the UCM at startup or if no data is received for a long time.

4.2.1.1 Practical results hardware modifications

The PC/104 is upgraded with the CAN-AC1-104 extension board. The Emerald MM 4 channel could not be removed due to a component overlap from the PC/104 main board and CAN extension board. The Emerald was left in between to ensure a well build-up system. The COM channels from the main board did not work with the Emerald extension board installed, so the Emerald board is still used to send position data to a PC. An additional header between the PC/104 main and CAN extension board could solve the problem and render the Emerald board useless. For now it remains in the system.
The reset lines needed for the UCM to start correctly are driven by 2 I/O lines from the Garnett MM 48-line digital I/O extension board. Only these two lines were not used in the controller. The lines could however not be connected directly to the reset lines from all the microcontrollers. The reset lines should be operated by an open collector gate which only pulls the line low when the input is high. The schematic below shows the components connected to the reset inputs of all the microcontrollers.

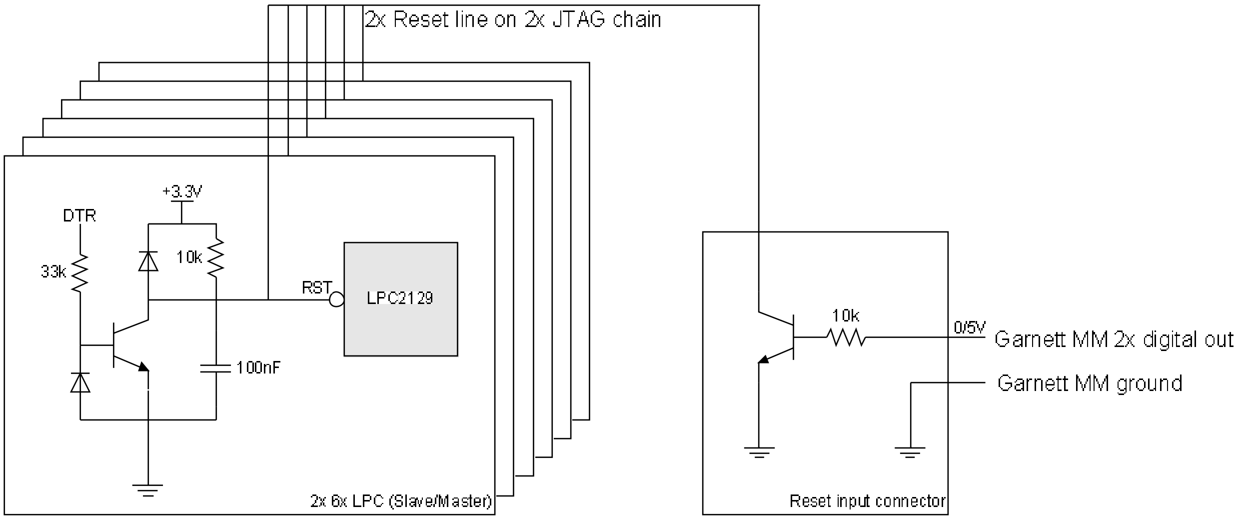


Figure 4.3 Reset interface UCM boards for each microcontroller (LPC)

All 6 reset lines from the master and slave LPC's [1] are tied together enabling an external device to reset all microcontrollers simultaneously. This gives 2 wires which have to be connected to two digital open collector outputs. The Garnett MM has high current pull-up/pull-down digital I/O's working with voltages of 0 and 5V, so the solution shown in Figure 4.3 is used. In order to reset the UCM both lines have to be operated in software as active high.

4.2.2 Software modifications

The software routines from the controller are a combination of M files, S files written in C and Simulink schematics. The xPC kernel is used to run the controller on the PC/104. The Simulink schematic will have to be modified and some coded blocks will be recoded. A manual how to create custom S files can be found in [3]. More detailed instructions how to use xPC can be found in Appendix A: xPC .

4.2.2.1 Practical results software modifications

All software changes are made in the MATLAB xPC model by adding blocks or changing custom written blocks. The model consists of several layers, each block can be examined to find another block under there or custom code. The top level consists of 3 blocks:

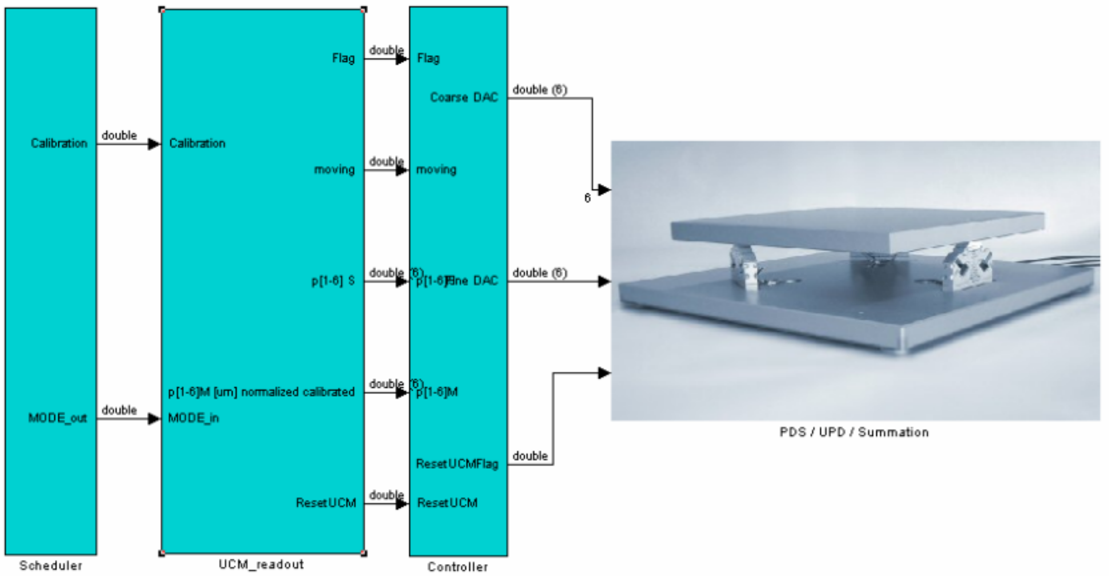


Figure 4.4 Top level controller

The only change in the top schematic is that the Reset UCM path is added. This path can reset the UCM system when no data is received for 5 minutes. Most changes are made in the biggest block called *UCM_readout*, formerly known as *UTI_readout*. Double-clicking this block gives a new schematic:

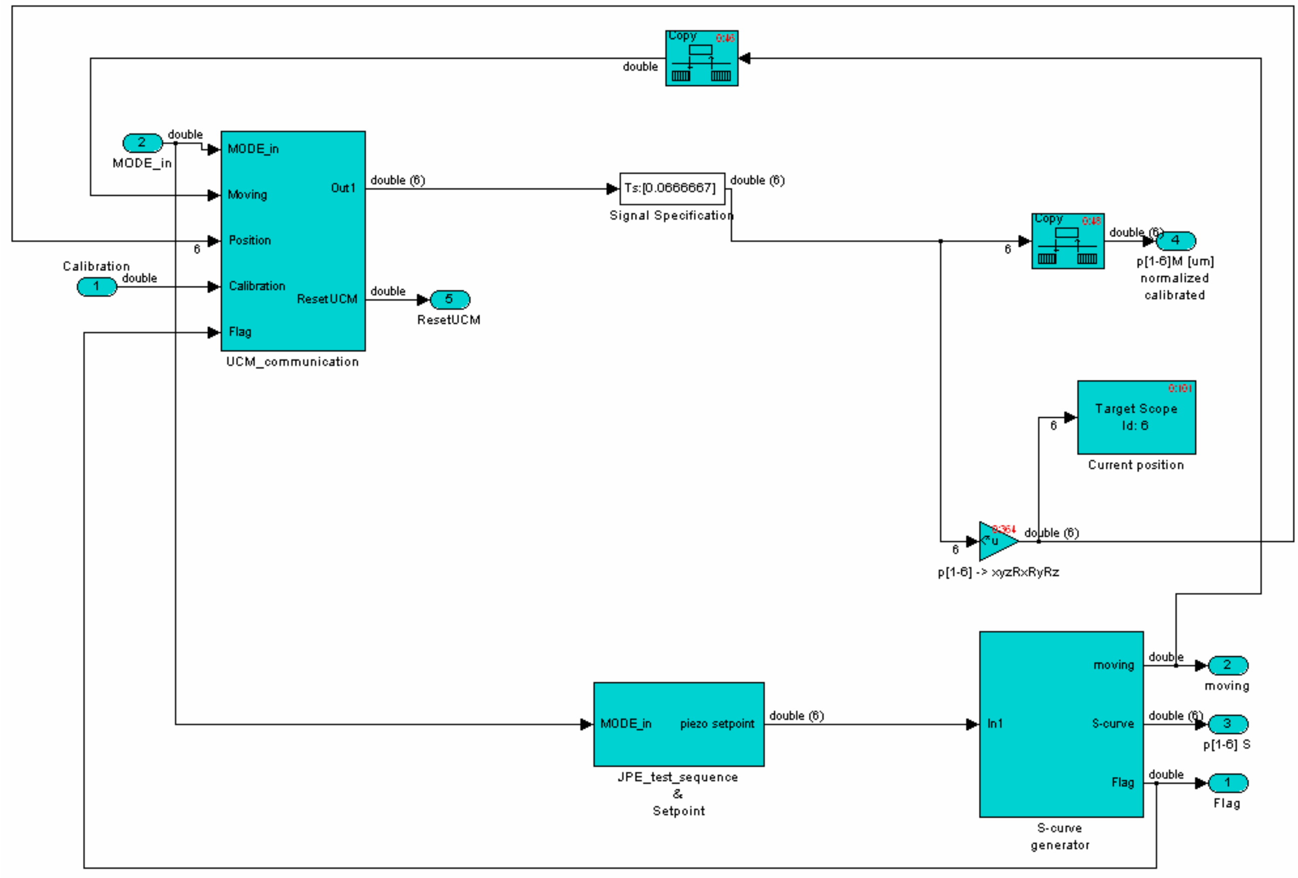


Figure 4.5 UCM_readout block

This block is still the same except for the *ResetUCM* output. Looking under the *UCM_communication* block reveals a new schematic:

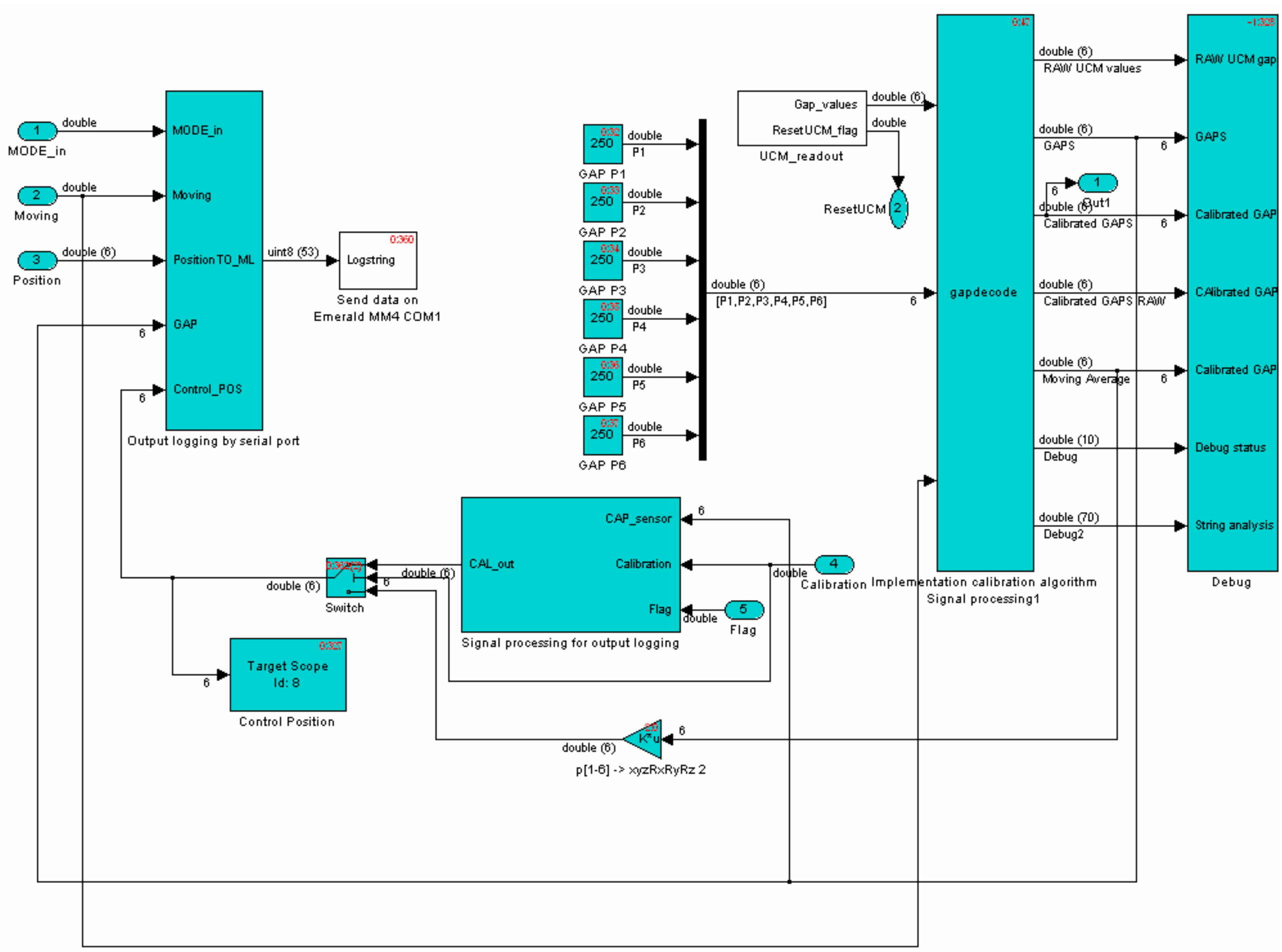


Figure 4.6 UCM_communication block

Instead of one block for the Emerald MM4 to send log data and receive sensor data there are now two separate blocks to readout the sensors and to send position data to a host. The block to send the position data to a host still contains the same Emerald MM4 communication block as before, only now the position data is transmitted on COM1 of the main board.
The *gapdecode* block, formerly named *asciidecode6*, has been recoded. Before this block processed an information string, now the gap values are immediately available at the input. The previous filter and process functionality have been maintained. Input values are simply checked if they are greater than zero, else the UCM has not sent any values yet, and if the received gap values are within the usable range.
The *UCM_readout* block provides the gap distance values; it has a bigger schematic inside and it is also responsible for creating the *ResetUCM* signal.
Figure 4.7 shows the schematic inside the block. Here a FIFO Setup block configures the CAN board with the Baud rate (1MBd), acceptance data and the correct address has to be set here. No acceptance mask is set since all the data on the CAN bus is going to the controller.
The FIFO read block gives with a fixed sample time 100 CAN frames, no matter how many frames have been received. This ensures timing integrity. If a message with the identifier 9 is received, the UCM system is ready to transmit data and a frame with identifier 2 is written in the CAN FIFO. The frame is sent on the CAN bus and all UCM PCB’s start to transmit their ADC data.
Depending on the identifier in the CAN message, the CAN messages are split in 6 groups if they contain sensor data. If a frame has no data, it’s not passed on. If several frames contain data with the same identifier, only the newest frame is passed on. These 6 streams are then multiplexed together to create an array of 6 sensor values in the correct order. These values are converted to gap distance values between the capacitor plates in the VeePAC modules and these values are transmitted out of the block.
The *FIFO Read RCV Level* block on the bottom left gives out the number of stored messages in the FIFO. If for any reason, more then 200 messages are stored here, the FIFO is emptied and reset, since only 255 messages can be stored. If any more messages arrive, they are simply lost. The *ResetUCM* block counts the number of times 0 messages are stored in the buffer. If the counter reaches 50000, the UCM is reset. This equals a time of 11 minutes if a sample time of 0.01333s is used.

The *ADC2GAP* block converts the received ADC value to a gap width in µm with the following equation:

$$V_{OUT_{MS3110}} = GAIN \times V2.25 \times 1.14 \times (C2_{IN} + CS2 - C1_{IN} - CS1)/CF + VREF =$$

$$5.13 \times (C2_{IN} - 4.9963 \times 10^{-12})/14.668 \times 10^{-12} + 2.25$$

$$ADC_{OUT} = ((5.13 \times (C2_{IN} - 4.9963 \times 10^{-12})/14.668 \times 10^{-12} + 2.25) - 2.5) \times \frac{2^{24}}{5}$$

$$C2_{IN} = 2.859259259 \times 10^{-12}(ADC_{OUT} \times \frac{5}{2^{24}} + 1.997410622)$$

$$G(\mu m) = \frac{\varepsilon A}{C2_{IN}} = \frac{8.854187818\, {}^{pF}\!/_{m} \cdot 55mm^2}{C2_{IN}(pF)}$$

$$G(\mu m) = \frac{486.98}{ADC_{OUT} \cdot 8.5213 \cdot 10^{-7} - 1.4670}$$

G(µm) = Gap distance between sensor plates expressed in µm

ADC = ADC discrete bit value in range of 0-2^{24}

Equation 4.1 Conversion ADC to gap width using default UCM settings & plate area of $55mm^2$

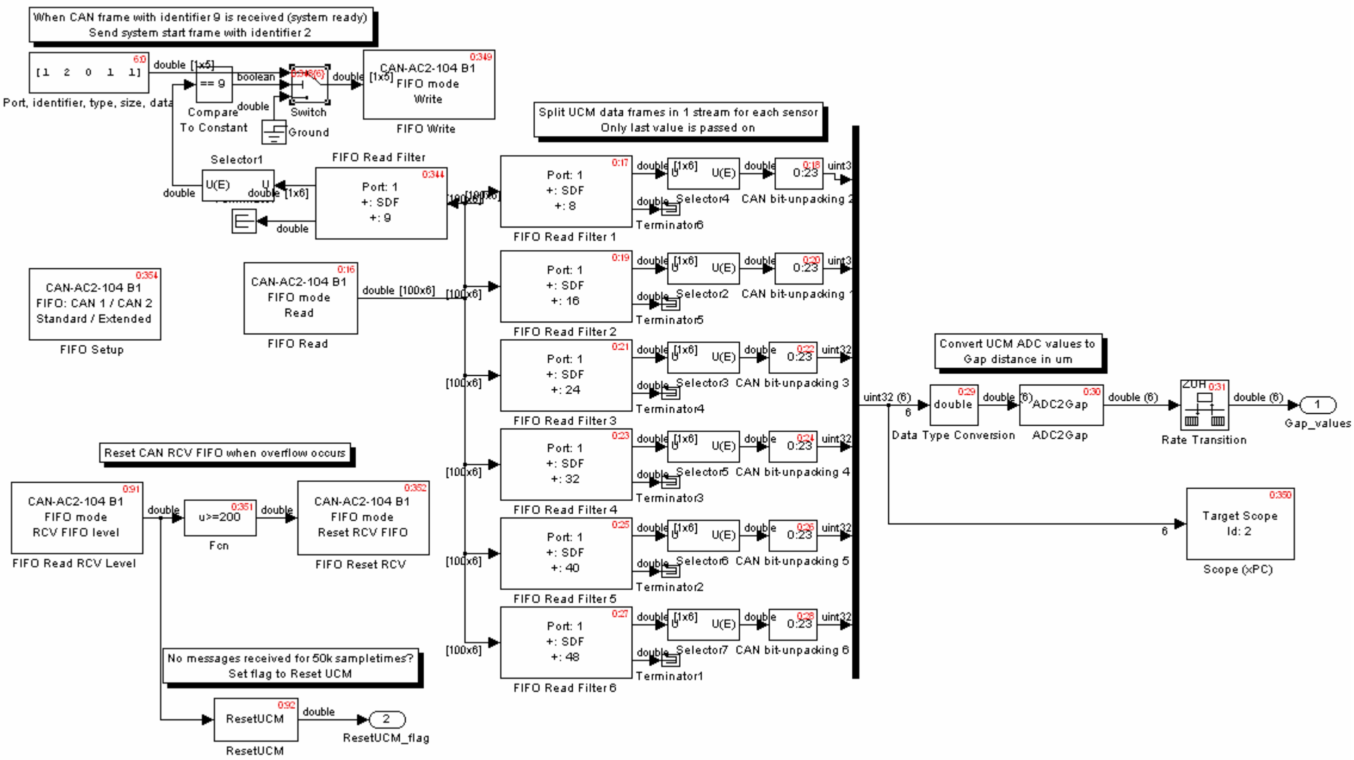


Figure 4.7 UCM_readout block

5 TESTS RESULTS UCM PROTOTYPE (UCM_01_0011A)

After a successful upgrade of the stage and controller to work with the UCM, the new performance has to be tested and can be compared to test results with the UTI. This chapter also contains additional tests with the UCM using fixed reference capacitors. More information about these capacitors can be read in "6.1 Ultra stable reference capacitors".
These tests are done to verify the UCM's performance and to provide more reliable test data than the tests done with unshielded fixed capacitors.

5.1 Test 1: compare UTI with UCM using LVDT reference probes

A resolution & stability test is already implemented in the piezo stage controller. The first test is to do this test with the controller which uses the UTI and after the UCM has been implemented in the system, the same test is done with the updated controller to check the new performance.

5.1.1 Test set up

The test is performed as described in [5]. The resolution and stability test is run from the controller and a PC logs the results of 6 Solartron LVDT probes placed in the stage. Results are limited by the 60nm resolution of the Solartron LVDT probes. The controller makes different steps alternating on each movement axis (Table 4.4) and the range of each axis is also tested. At the end, all axes are attempted to be kept in a 0 position to test the stability. The total test set-up is shown in Figure 4.1 for the UTI and in Figure 4.2 for the UCM. Only instead of the controller information, the LVDT's positions are logged.

5.1.2 Measurement procedure

The procedure is as described in [5]. Test results are processed offline in a Labview application. Visual interpretation of the graphs created with this application gives the numbers from tables Table 5.1 through Table 5.6.

5.1.3 Test results

5.1.3.1 Results controller with UTI as measurement system (Reference measurement)

Table 5.1 Measured stroke of the table in global coordinates.

DOF	- Stroke	+ Stroke
x [µm]	-84	71
y [µm]	-64	56
z [µm]	-67	80
Rx [µrad]	-866	960
Ry [µrad]	-860	1113
Rz [µrad]	-784	740

Table 5.2 Measured stability of the table in global coordinates.

DOF	Stability for dT < ±0.05 ºC, dt = 1 hour
x [µm]	< 0.100
y [µm]	< 0.100
z [µm]	< 0.200
Rx [µrad]	< 1
Ry [µrad]	< 1
Rz [µrad]	< 1

Table 5.3 Measured resolution of the table in global coordinates.

	Resolution
x [µm]	< 0.100
y [µm]	< 0.100
z [µm]	< 0.100
Rx [µrad]	< 2
Ry [µrad]	< 2
Rz [µrad]	< 2

5.1.3.2 Results controller with UCM as measurement system

UCM is set to sample 50Hz/sensor with average filter of 10x.

Table 5.4 Measured stroke of the table in global coordinates.

DOF	- Stroke	+ Stroke
x [µm]	-86	88
y [µm]	-87	89
z [µm]	-83	85
Rx [µrad]	-1296	1317
Ry [µrad]	-1113	1159
Rz [µrad]	-846	930

Table 5.5 Measured stability of the table in global coordinates.

DOF	Stability for dt < ±0.05 ºC, dt = 1 hour
x [µm]	< 0.06
y [µm]	< 0.06
z [µm]	< 0.08
Rx [µrad]	< 0.7
Ry [µrad]	< 1.1
Rz [µrad]	< 0.8

Table 5.6 Measured resolution of the table in global coordinates.

	Resolution
x [µm]	< 0.100
y [µm]	< 0.100
z [µm]	< 0.100
Rx [µrad]	< 0.5
Ry [µrad]	< 0.5
Rz [µrad]	< 0.5

5.1.4 Test conclusion

The measured strokes in global coordinates from both measurement systems match each other; so it can be concluded that the UCM gives reliable information regarding the position of the stage. Only the UTI results show an asymmetrical range, this could be due to some offsets in the center position of the stage (ill calibrated).
Improvements can be seen in the stability and the resolution, but the used reference sensors do not have the resolution needed to provide reliable test data. Most performance now can be seen in the resolution of the rotating axes. New tests will no longer include the data from the LVDT sensors, but only the data from the measurement system itself. This due to the limited resolution of the LVDT probes, 60nm, which cannot provide accurate performance data.

5.2 Test 2: compare UTI with UCM using controller information

A resolution & stability test is already implemented in the controller. Instead of using the position information obtained by the LVDT probes; the controller information is used which uses the actual UTI and UCM measurements. The UCM samples with 50Hz and has a running average filter of 10x implemented. The controller and system setup with the UCM are further identical to the UTI test setup and controller. It should be noted that the sample frequency of the UTI is much lower.

5.2.1 Test set up

In this test the controller with connected piezo stage is used. In one run the UTI is used as the capacitive measurement system and in another run the UCM is used as the capacitive measurement system. The resolution and stability test is run from the controller and a PC logs the results of the controller information output on COM1.This information includes current position and gap width. The controller logs the data with a speed of 5 Hz. All results are logged in nm and nRad's. The last log file from the controller with the UTI implemented is used as a reference. The controller is in both runs identical, except for its communication routines. The total test set-up is shown in Figure 4.1 for the UTI and in Figure 4.2 for the UCM.

5.2.2 Measurement procedure

Both log files are split in one log file containing only the position and time information and another one containing the gap widths and time information. A MATLAB script then analyzes both files and shows a few graphs with some typical numbers. The numbers displayed in the graphs are obtained using the following mathematical functions:

Dynamic range (C): Capacitive dynamic capacitive range. This is the total theoretical range, 10pF, divided by the 3σ deviation expressed in pF. It is assumed that the smallest change in capacity here equals the 3σ deviation expressed in pF. A value of 10^5 corresponds with a resolution of 100aF.

$$C(pF) = \varepsilon_0 \varepsilon_r \frac{A}{d} = \frac{486.98}{d(\mu m)}$$

$$3\sigma(pF) = \frac{486.98}{d(\mu m)} - \frac{486.98}{d(\mu m) + 3\sigma(\mu m)} = \frac{486.98(d(\mu m) + 3\sigma(\mu m))}{d(\mu m)(d(\mu m) + 3\sigma(\mu m))} - \frac{486.98 d(\mu m)}{d(\mu m)(d(\mu m) + 3\sigma(\mu m))}$$

$$3\sigma(pF) = \frac{486.98 \times 3\sigma(\mu m)}{d(\mu m)^2 + d(\mu m) \times 3\sigma(\mu m))}$$

$$DR_C = \frac{10pF}{3\sigma(pF)}$$

$$\mathrm{d}(\mu\mathrm{m}) = \text{Gap distance between sensor plates expressed in } \mu\mathrm{m}$$

$$\varepsilon_0(\mathrm{F/m}) = \text{permittivity of free space, equals } 8.854187 \times 10^{-12}\ F/m$$

$$\varepsilon_r(\mathrm{F/m}) = \text{relative static permittivity of the material between the plates, 1 for vacuum}$$

$$\mathrm{A}(\mathrm{m}^2) = \text{overlapped sensor area}$$

Equation 5.1 Calculation dynamic capacity range assuming 0-10pF range

NFR (C): The needed noise free resolution expressed in bits to achieve to capacitive dynamic range.

$$NFR(bits)_C = {}^2\log(DR_C)$$

Equation 5.2 Capacitive noise free resolution

Dynamic range (ADC): Dynamic range calculated from ADC codes. This is the total ADC range, 2^{24}, divided by the 3σ deviation expressed in bits. It is assumed that the smallest change detectable in ADC values here equals the 3σ deviation expressed in a bit value. Since the total ADC range covers more than 0-10pF, the dynamic range should be bigger than the previously calculated dynamic range.

$$ADC = \frac{A}{G(\mu m) \times B} + \frac{C}{B}$$

$$3\sigma(ADC) = \frac{A}{G(\mu m) \times B} + \frac{C}{B} - \left(\frac{A}{(G(\mu m) + 3\sigma(\mu m)) \times B} + \frac{C}{B} \right) =$$

$$3\sigma(ADC) = \frac{A}{G(\mu m) \times B} - \frac{A}{(G(\mu m) + 3\sigma(\mu m)) \times B} = \frac{A \times B \times 3\sigma(\mu m)}{B(B(G(\mu m) + 3\sigma(\mu m)))}$$

$$3\sigma(ADC) = \frac{A \times B \times 3\sigma(\mu m)}{(B \times G(\mu m))^2 + B^2 \times G(\mu m) \times 3\sigma(\mu m))}$$

$$DR_{ADC} = \frac{2^{24}}{3\sigma(ADC)}$$

$G(\mu m)$ = Gap distance between sensor plates expressed in µm

ADC = ADC discrete bit value in range of $0 - 2^{24}$

$A = 486.98$, $B = 8.5213 \cdot 10^{-7}$, $C = 1.4670$

(Values come from inverted conversion from ADC value to gap width in µm)

Equation 5.3 Calculation dynamic ADC range using actual full scale ADC input

NFR (ADC): The needed noise free resolution expressed in bits to achieve to ADC dynamic range

$$NFR(bits)_{ADC} = {}^2\log(DR_{ADC})$$

Equation 5.4 ADC noise free resolution

5.2.3 Test results

A more extensive test report containing all the graphs can be found in [6]. The stability is examined when the PCS is set control its position around 0 on all axes. Table 5.7 and Table 5.9 show the most important results. The calculation of the values in Table 5.7 is explained in 5.1.2 Measurement procedure.

5.2.3.1 Stability long term

Last log file from UTI contains only data where position is fixed for 420 seconds. These results are compared to a log file from UCM with length of 10000 seconds in fixed position.

Table 5.7 Results performance UCM compared to UTI using controller data

	DR_C UTI	DR_C UCM	NFR_T UTI	NFR_T UCM	DR_{ADC} UTI	DR_{ADC} UCM	NFR_{ADC} UTI	NFR_{ADC} UCM
Sensor 1	7126x	42285x	12.80 bits	15.37 bits	10188x	60451x	13.31 bits	15.88 bits
Sensor 2	7940x	47815x	12.95 bits	15.55 bits	11352x	68356x	13.47 bits	16.06 bits
Sensor 3	7206x	48896x	12.81 bits	15.58 bits	10302x	69903x	13.33 bits	16.09 bits
Sensor 4	8386x	39421x	13.03 bits	15.27 bits	11963x	56357x	13.55 bits	15.78 bits
Sensor 5	10559x	48558x	13.37 bits	15.57 bits	15096x	69420x	13.88 bits	16.08 bits
Sensor 6	8182x	49082x	13.00 bits	15.58 bits	11698x	70170x	13.51 bits	16.10 bits

The same data translated to position info can be used to give some information regarding the stability over a long period of time in position coordinates.

Table 5.8 3σ values expressed in nm and nrad for UTI and UCM

DOF	Stability for dT < ±0.1 ºC UTI (3σ)	UCM (3σ)
x [nm]	48.0	7.2
y [nm]	41.8	8.6
z [nm]	52.5	6.3
Rx [nrad]	79.1	11.5
Ry [nrad]	56.1	14.8
Rz [nrad]	34.8	6.4

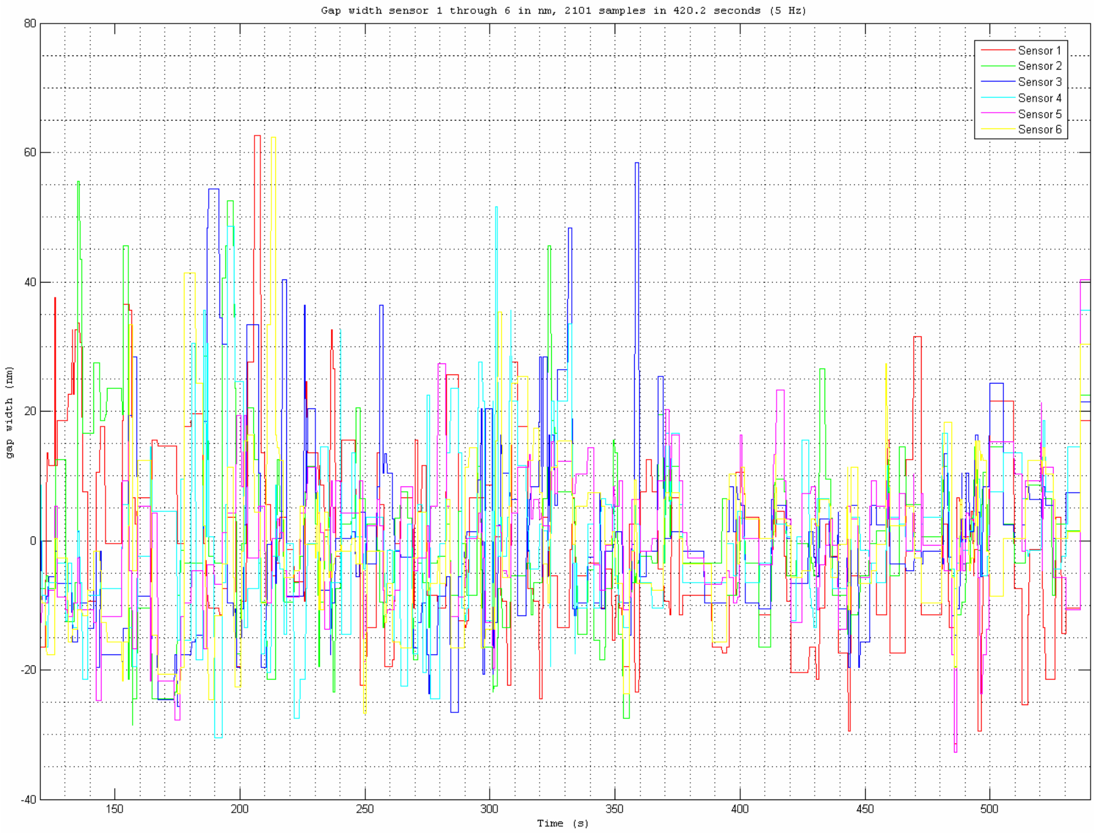


Figure 5.1 Graphical log UTI 6x sensor output for 420 seconds translated in gaps

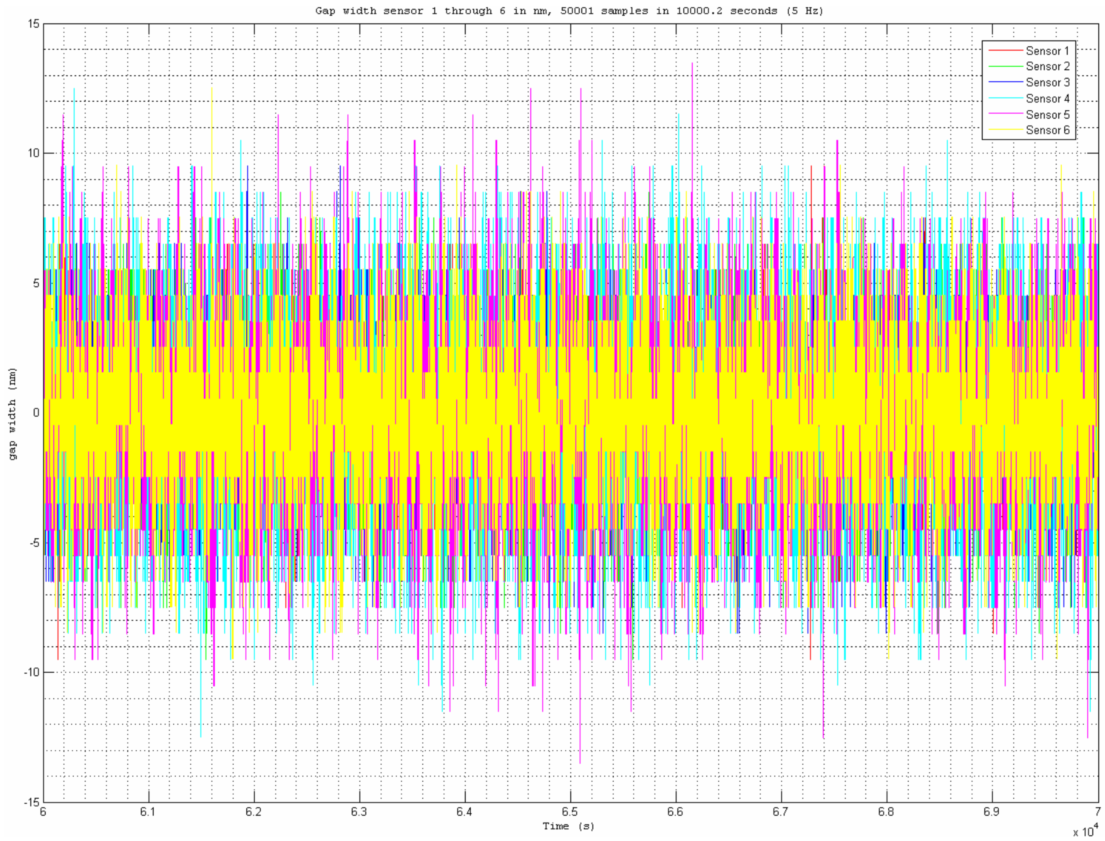


Figure 5.2 Graphical log UCM 6x sensor output for 10,000 seconds translated in gaps

5.2.3.2 Stability short term (1 minute)

Last log file from UTI is analyzed now for the same period, only in time windows of 60 seconds each after which the mean is calculated for the results off all time windows together. The same applies for the UCM log file.
Figure 5.3 and Figure 5.4 show the time plot for 60s for the UTI and UCM to show the difference in bandwidth.

Table 5.9 Results performance UCM compared to UTI using controller data

	DR_C UTI	DR_C UCM	NFR_T UTI	NFR_T UCM	DR_{ADC} UTI	DR_{ADC} UCM	NFR_{ADC} UTI	NFR_{ADC} UCM
Sensor 1	10777x	44619x	13.40 bits	15.45 bits	10188x	60451x	13.31 bits	15.88 bits
Sensor 2	11544x	52507x	13.49 bits	15.68 bits	11352x	68356x	13.47 bits	16.06 bits
Sensor 3	14297x	48933x	13.80 bits	15.58 bits	10302x	69903x	13.33 bits	16.09 bits
Sensor 4	15750x	41905x	13.94 bits	15.35 bits	11963x	56357x	13.55 bits	15.78 bits
Sensor 5	12479x	57280x	13.61 bits	15.81 bits	15096x	69420x	13.88 bits	16.08 bits
Sensor 6	17602x	58351x	14.10 bits	15.83 bits	11698x	70170x	13.51 bits	16.10 bits

The same data translated to position info can be used to give some information regarding the stability over a short period of time in position coordinates.

Table 5.10 3σ values expressed in nm and nrad for UTI and UCM

DOF	Stability for dT < ±0.05 °C UTI (3σ)	UCM (3σ)
x [nm]	25.3	6.5
y [nm]	22.2	8.4
z [nm]	41.4	5.4
Rx [nrad]	37.4	9.8
Ry [nrad]	27.9	12.2
Rz [nrad]	20.6	6.4

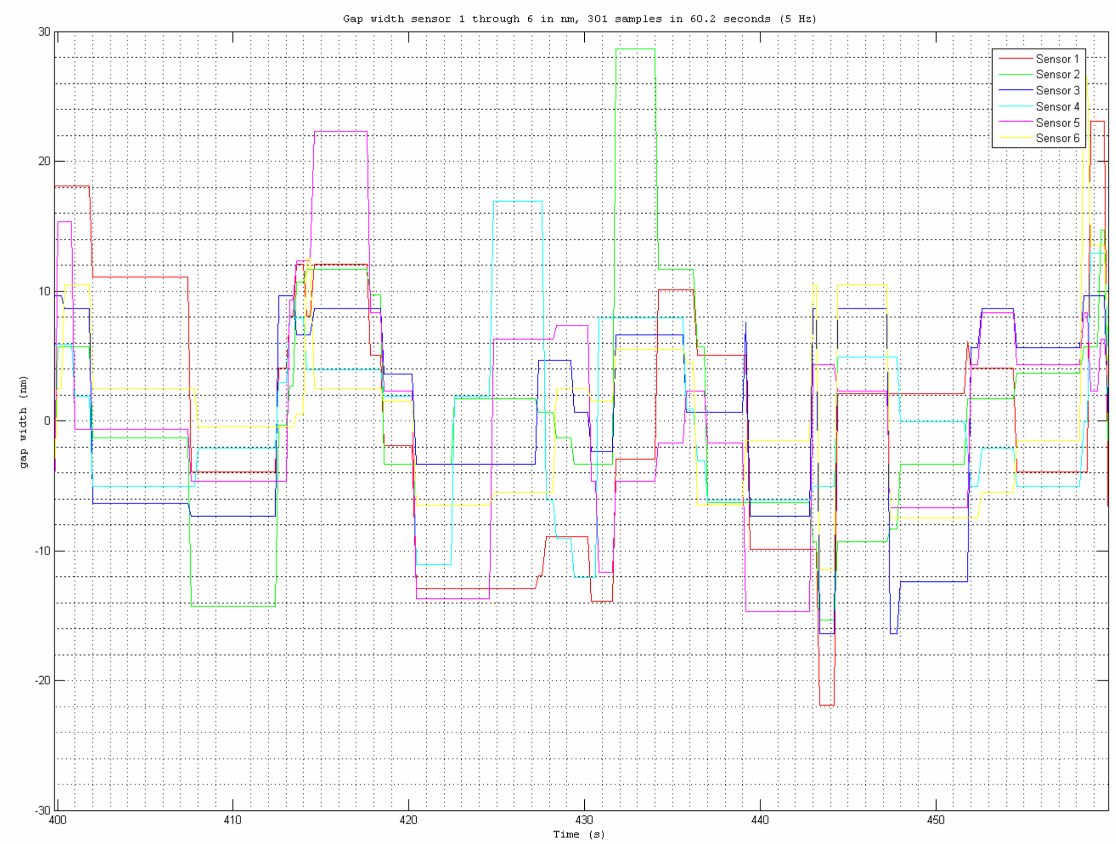


Figure 5.3 Graphical log UTI 6x sensor output for 60 seconds translated in gaps

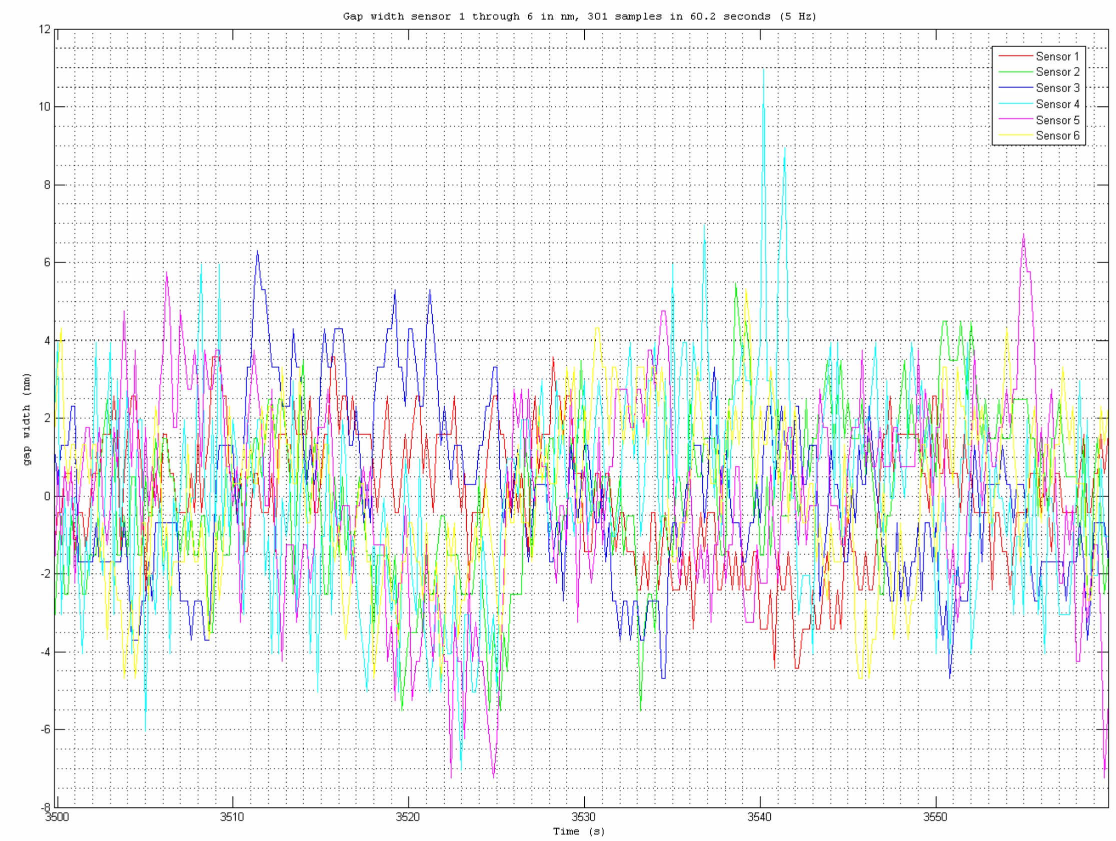


Figure 5.4 Graphical log UCM 6x sensor output for 60 seconds translated in gaps

5.2.4 Test conclusion

On a short term basis, the UCM has a dynamic range about 3.7 times the dynamic range of the UTI. On a long term basis, this ratio is increased to 5.6x. This is the improvement in capacitive measurement capabilities. The observed deviations on the UCM are too small to be detectable by the 60nm reference LVDT's, therefore all further tests will only include the UCM results, logged from the controller itself.
Both controllers using UTI and UCM system, use the same sample frequencies, so regarding the bandwidth: the controller which uses the UTI has a limited bandwidth due to the UTI's sample frequency, the controller which uses the UCM is limited by the bandwidth from the controller. (Compare Figure 5.3 with Figure 5.4.) More tests will show the maximum bandwidth possible with the UCM implemented. The UTI will no longer be included in test data, since the UCM outperforms the UTI approximately 4 times at a higher sample frequency.
It is not clear yet whether the results with the UCM implemented are limited by the UCM, the controller or the piezo power supply. More tests will provide a better insight in the capabilities of the UCM.

5.3 Test 3: examine UCM's performance using shielded reference capacitors

To get an idea of the limitations of the PCS in combination with the UCM, the PCS is disconnected from the UCM and the same measurements are done as in test 2.

5.3.1 Test set-up

Piezos and capacitive sensors are disconnected from the amplifier and UCM. Fixed capacitors inside an aluminum case as described in 6.1 Ultra stable reference capacitors. Shielded wires are used from UCM case to aluminum box. The wires are connected to the box with BNC connectors and the capacitors are placed directly on the BNC connector. Only the controller is used with the UCM connected by a CAN bus and reset lines.
The UCM is set to sample with 50Hz; the ADC on each UCM releases new data with 50Hz. Each ADC samples with 30kHz and averages 500 measurements for each output value. This data is also filtered by the microcontroller with a running average filter of 10 samples. Figure 5.5 shows a simplified scheme of the test setup. These are the same UCM settings as in the previous test. Please note that the MS3110 input chip limits the input signal bandwidth to 500Hz by a 2nd order low pass filter.

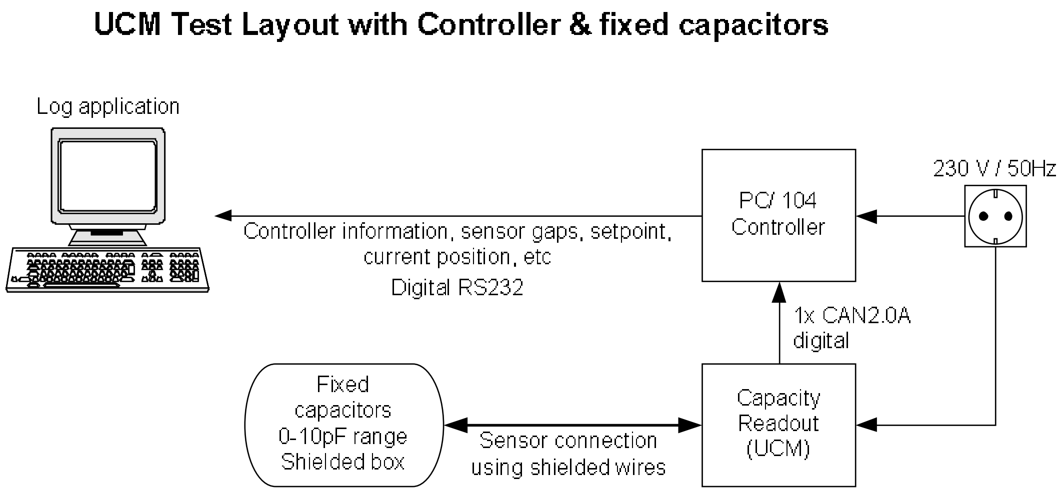


Figure 5.5 Test setup UCM with controller and fixed capacitors

5.3.2 Measurement procedure

The controller generates a log with gap width data from each sensor. This log is captured with LABVIEW and converted to a file with only the gap width data and timing references. This log file is analyzed in MATLAB. The connected capacitors on each UCM have a different value and are rotated each setting. All measurement data is collected for each sensor for a short time (60s) with the various input capacities and different graphs can be created with data obtained during these tests.

5.3.3 Test results

The graphs below are a presentation of the fitted data results. Five measure points are available for each graph; fixed capacitors of 1.8pF, 3.3pF, 5.6pF, 6.8pF and 9.8pF. A second degree polynomial is fitted on these points to create the graphs. The results apply to data analyzed with non-overlapping time windows of 60 seconds.

Figure 5.6 shows the 3σ values in aF(10^{-18})for each UCM versus the input capacity. UCM 4: top curve, UCM 5: bottom curve.
Figure 5.7 shows the actual noise free resolution for each UCM versus the input capacity. The values are calculated using Equation 5.4. UCM 5: top curve, UCM 4: bottom curve.
Figure 5.8 is a different interpretation of Figure 5.6. The input capacity is divided by the 3σ values to create a dimensionless S/N ratio. UCM 5: top curve, UCM 4: bottom curve.

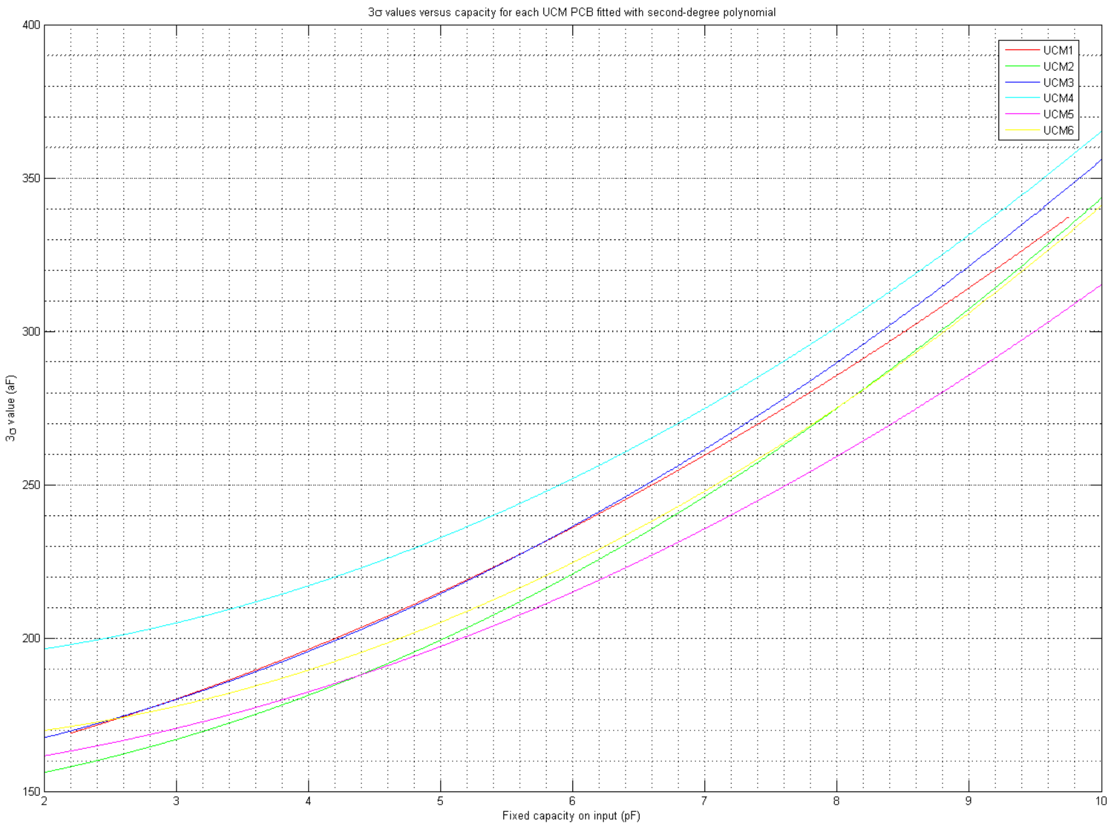


Figure 5.6 3σ values in aF(10^{-18}) for each UCM versus the input capacity

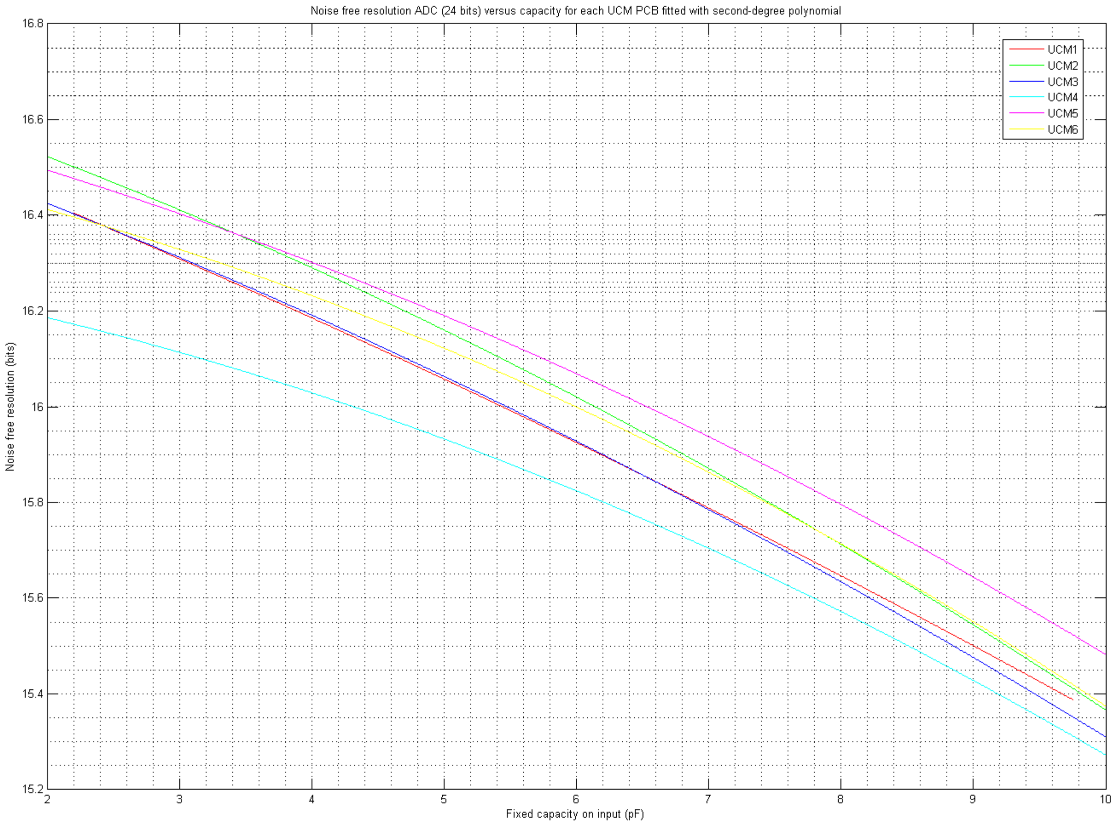


Figure 5.7 Actual noise free resolution for each UCM versus the input capacity

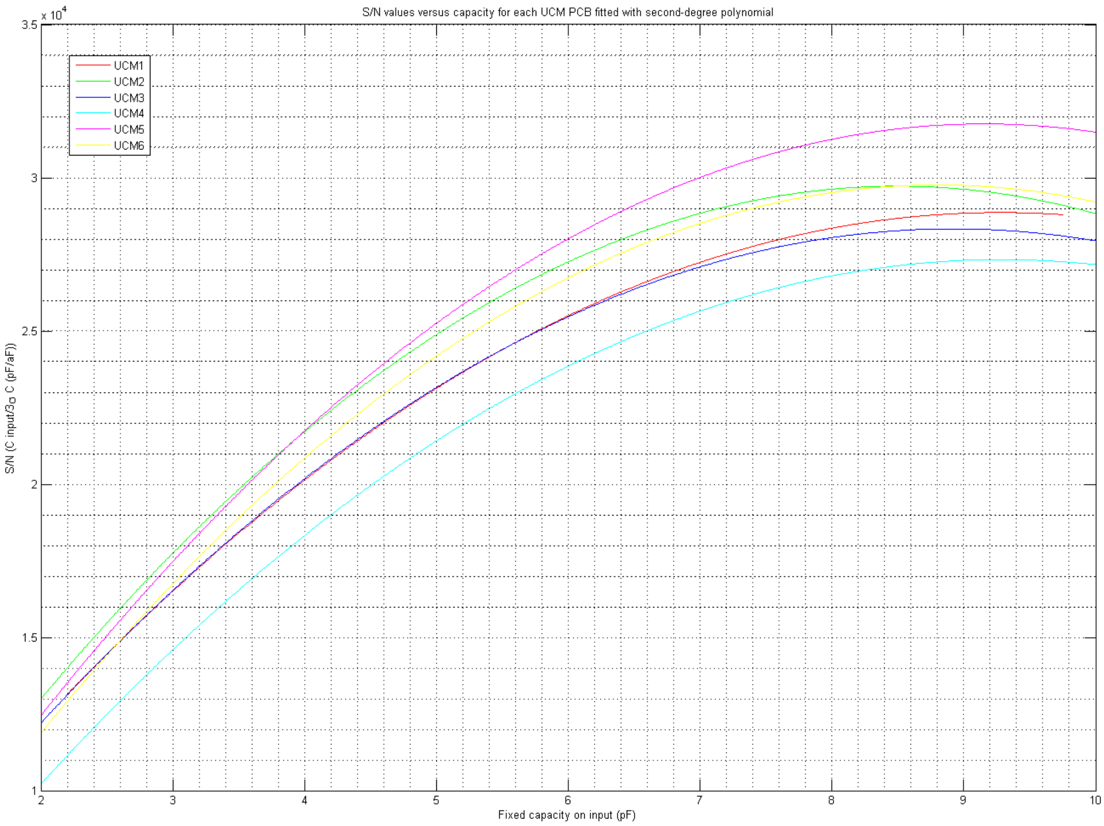


Figure 5.8 Input capacity divided by 3σ values for each UCM versus the input capacity (signal/noise ratio)

5.3.4 Test conclusion

The obtainable resolution not only depends on the input capacity value, but also on the used UCM PCB. Although it looks like the spread between various PCB's has been increased after all PCB's have been placed in one case, it still might be possible that the differences also occurred before. The measurement procedure outside the case could have added the same amount of noise to each UCM PCB, making it impossible to measure the smallest resolution possible, merely giving the same noise read-out for each PCB. Testing the PCB's inside a case with 6 capacitors soldered onto a sub-d connector connected to the sub-d connector input introduces crosstalk inside the case, but even more between all the capacitors legs.
The test done here provides an accurate performance image of all the UCM's working together in one case. A satisfactory explanation for the big performance difference between UCM 5 & 4 has still to be investigated.
When comparing the results from 'Test 2: compare UTI with UCM using controller information' to 'Test 3: examine UCM's performance using shielded reference capacitors', it can be seen that there are little performance differences with the active controlled stage used with its capacitive sensors and the shielded fixed capacitors. The control part of the stage can introduce some noise as well as the whole construction; the shielded reference capacitors are a more stable reference although differences are small (+/-10aF). Since also the same variations occur in different UCM measurements in both cases, it can be concluded that the stage's performance is still limited by the UCM. Improving the controller will surely improve the dynamic capabilities of the stage, but for a better static performance, the UCM has to be improved. Improvements can be achieved by redesigning the case (separate connectors, shielding from power supply, less wires inside) as well as redesigning the UCM itself. Most performance can be won by carefully examining the UCM layout and better handling of the MS3110.

5.4 Test 4: UCM's performance versus sample frequency

This test is the same as 'Test 3: examine UCM's performance using shielded reference capacitors', only now the results are directly logged from the UCM real-time at a much higher sample frequency. Results are offline analyzed.

5.4.1 Test set up

The UCM case with the 6 UCM's inside is used and still connected to the controller. The controller is only used to reset the UCM and observe system operation. A separate microcontroller board (MCB2100) is connected to the CAN-bus as a listen-only node. The MCB2100 is connected to a PC using RS232 communication with the highest baud rate possible. An USB-to-RS232 FTDI cable is used with a Baud rate of 375kBd. Each UCM samples with 2kHz and only the 3 bytes ADC-data with one byte to indicate PCB used is sent on the COM-link. Equation 5.5 shows that it is possible to transmit up to 9.3k samples/s.

$$\begin{aligned}&\text{375kBd communication}\\&\text{10Bd needed for one byte}\\&smpls/s = \frac{375kBd}{10Bd} \Big/ 4B = 9{,}375\,smpls/s\end{aligned}$$

Equation 5.5 Highest real-time transmission sample rate on COM-port

The MCB2100 has to be flashed with the contents of project '*G:\JPE\Control\UniversalCapacityMeasurementIntegration\WERKdir_SW\03_KEILfiles\\FIRMWARE UCM HOST VERSION 2.0\firmware_UCM_host.Uv2*'.The aluminum box with the 3.1pF capacitor is connected to each UCM and switched to the next one after each test. Figure 5.9 shows the test setup, the controller is replaced by the MCB2100 to log faster.

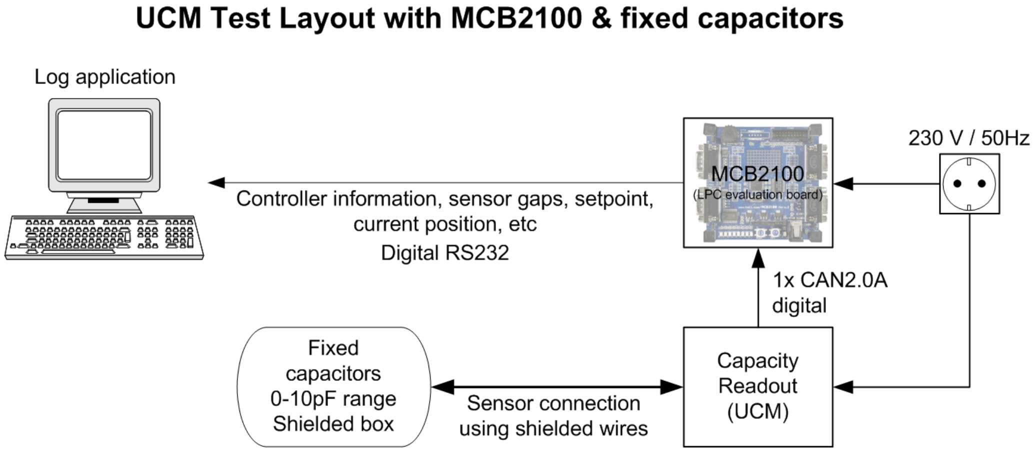


Figure 5.9 Test setup UCM with fixed capacitors and MCB2100

5.4.2 Measurement procedure

If all hardware is connected and powered on, a LABVIEW application can be started to communicate with the MCB2100 and log raw data. By transmission of 1-6 one UCM is selected to transmit sample data real-time to the PC and a log file is created. Retransmission of 1-6 will disable transmission for that UCM. The log file, which only contains binary data and an ASCII number for the UCM number, has to be converted to an ASCII file with time reference before it can be processed in MATLAB. The included UCM numbers in the log file are used to check the log file for consistency when converting the log. The converted log is loaded in a MATLAB script which analyzes the logs in 1s windows by finding the 3σ values in attofarads for each window and then averages the values for the number of windows. Data is then sampled down and the same 3σ analysis is performed for the data with lower sample rate (2 following samples become 1 sample, then 3 following samples become 1 sample, and so on). This conversion in sample rate would be the same method the ADC on the UCM uses when a lower sample frequency is selected. An FFT analysis can also be done to get an idea of the frequency contents of the data. Previous tests could not be analyzed in the frequency domain, since they were not logged real-time.

5.4.3 Test results

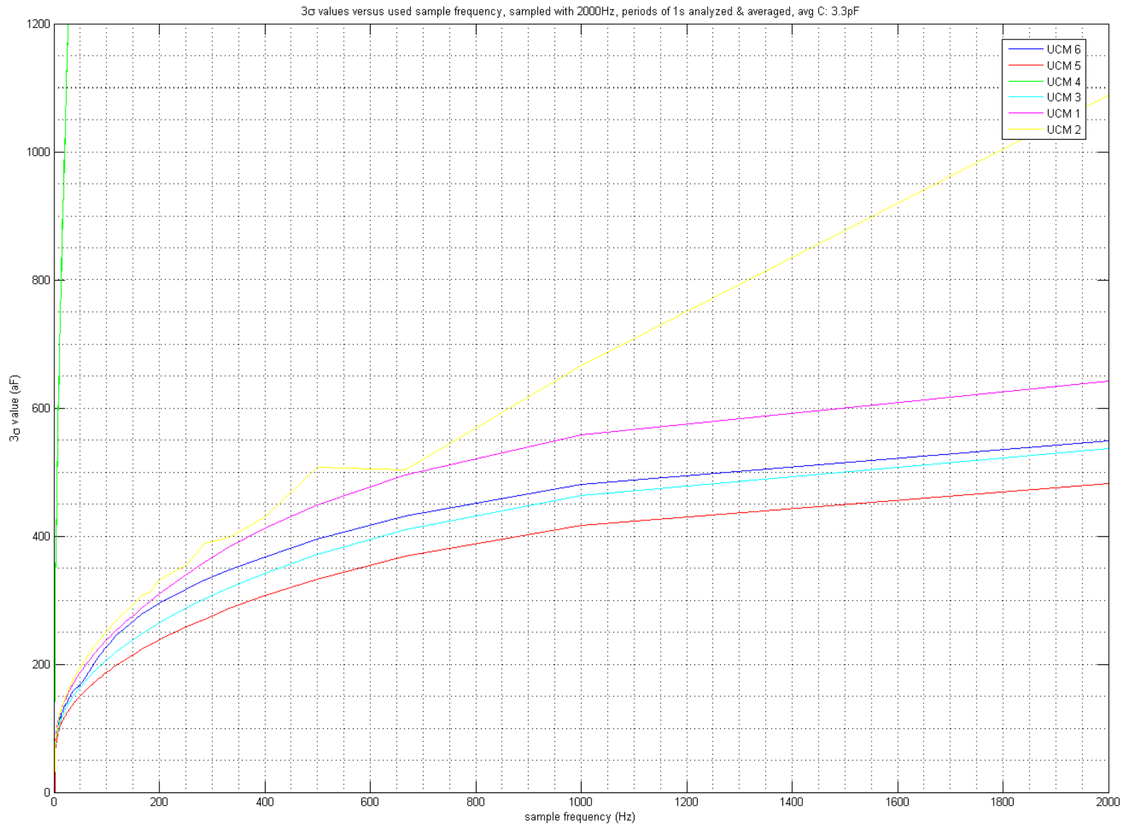


Figure 5.10 3σ values in aF versus used sample frequency by sampling data rate offline down

Four UCM's show comparable results, but two UCM's are performing very poorly, especially number 4, which goes off the graph. An FFT analysis shows that there is a lot of noise present in this UCM's signal. A signal to noise ratio value in dB's calculated from this plot equals 26.08dB.

$$SNR = 10 \times {}^{10}\log \frac{F(0)}{\sqrt{F(1)^2 + F(2)^2 + F(3)^2 + \ldots}}$$

Equation 5.6 Signal-to-noise ratio in dB's

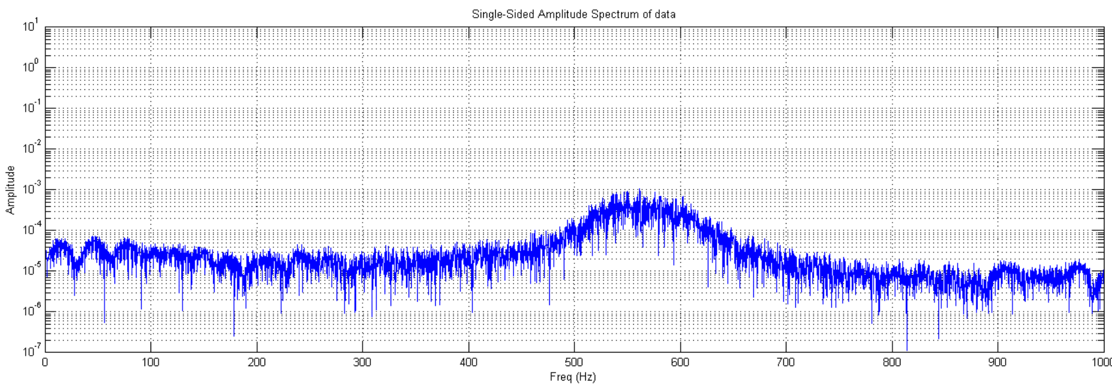


Figure 5.11 FFT analysis of first 8192 samples of UCM 4 sampled with 2kHz

A typical FFT graph can be seen in Figure 5.12. This graph has an SNR of: 44.26dB.

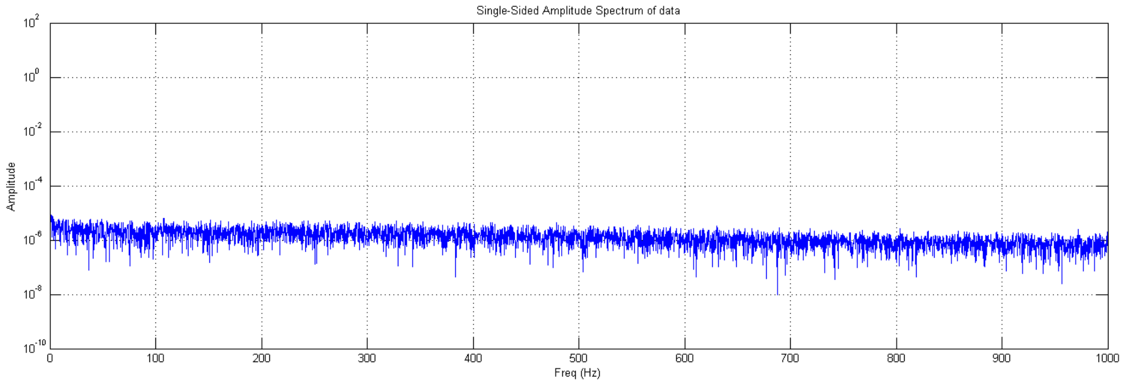


Figure 5.12 FFT analysis of first 8192 samples of UCM 5 sampled with 2kHz

An investigation of the case gives more insight in the UCM's performance differences. When all cables are disconnected from all UCM's, they share a much more common characteristic (Figure 5.14). If all the excitation frequencies generated by the MS3110 on each PCB are also trimmed to 100kHz (+/- 5kHz), their performance even draws closer to each other (Figure 5.15, only UCM 6 shows some spikes around 50Hz, this UCM is placed next to AC power inlet (230VAC, 50Hz)). Varying the excitation frequency of each MS3110 allows to find the best results for each separate UCM. Also varying the excitation frequency enough between different UCM's, eliminates a great deal of crosstalk, since all UCM's share a 25 pins sub-d connector to the outside world. The frequencies of UCM 2 and 4 are so close to each other that they introduce a lot of crosstalk between the UCM's inputs of these PCB's coupled in the sub-d connector.
Varying the frequencies gives a wider spread in frequency for the crosstalk which improves the average results for all the UCM's together. This improvement can be seen by comparing the best and worst SNR from before and after varying the excitation frequency:

Before:	Worst:	26.08dB	Best:	44.26dB
After:	Worst:	38.54dB	Best:	44.29dB

Figure 5.13 shows the result when creating the same graph as in Figure 5.10. In order to get the characteristics even closer to each other, a redesign of the case is needed with separate BNC connectors for each UCM and individually trimmed MS3110's on each PCB.

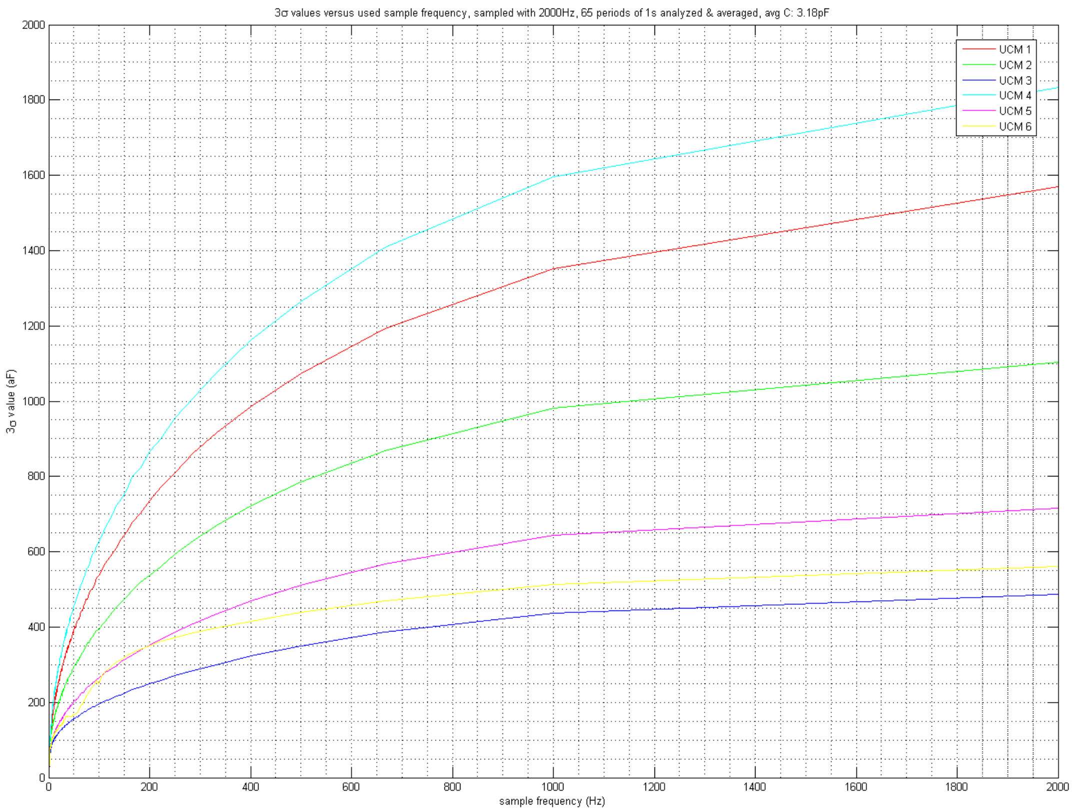


Figure 5.13 3σ values in aF versus used sample frequency after modifying MS3110 settings

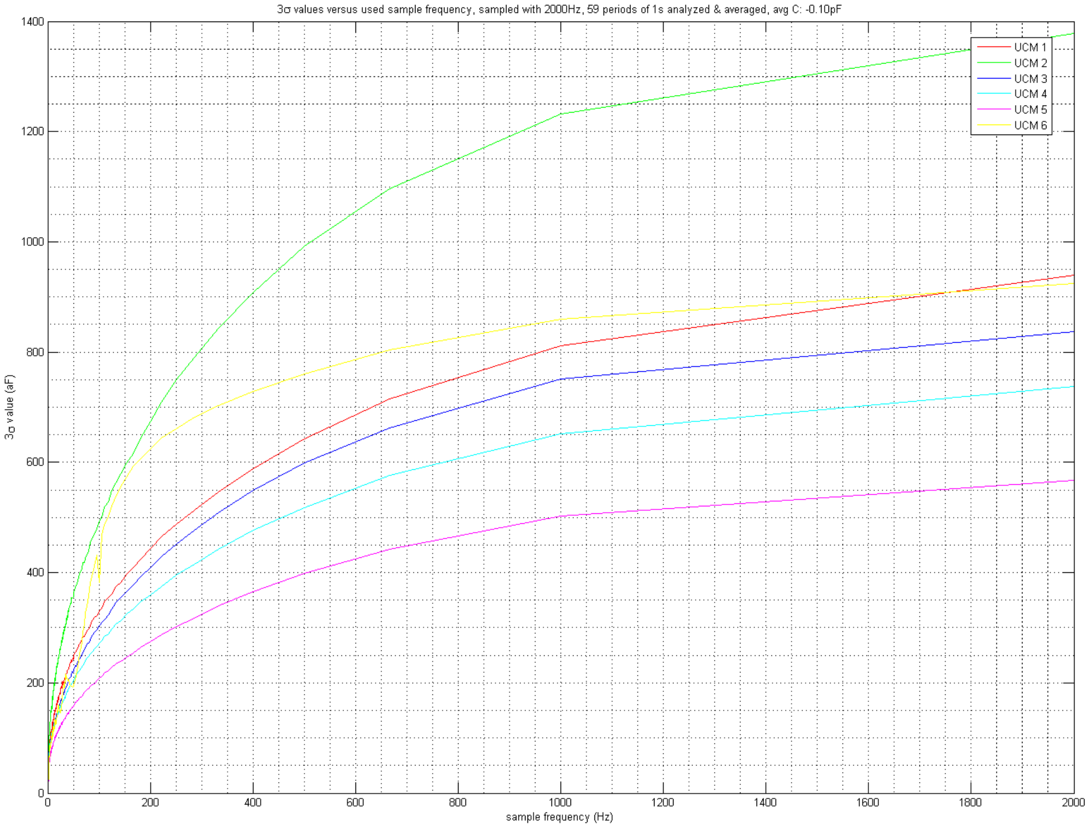


Figure 5.14 3σ values in aF versus used sample frequency with wires & capacities disconnected from UCM's

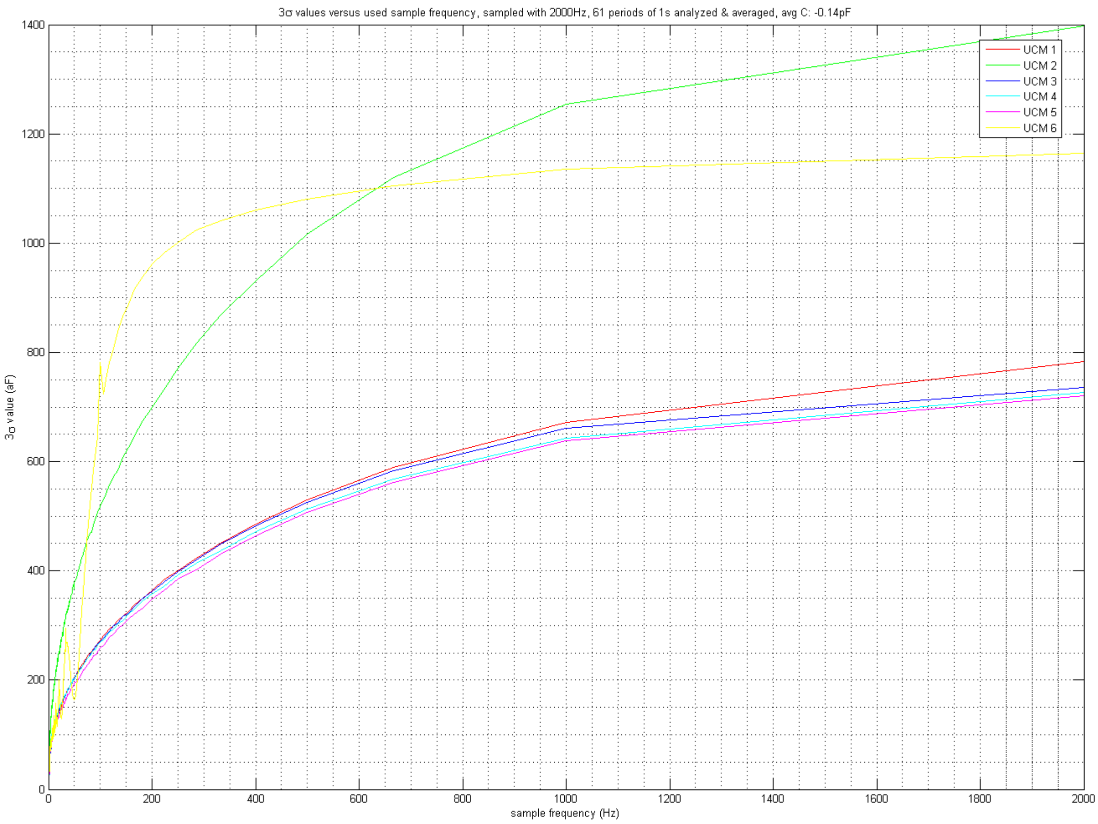


Figure 5.15 Same plot and setting as Figure 5.14, only now with trimmed excitation frequency

The same data is analyzed after processing it with a 40 points average filter which gives the graph in Figure 5.16. This filter should suppress 50Hz and multiples, which are present on UCM 6, to give the best comparison of all 6 UCM's. With this filter, the 3σ values are the same when sampling with 500Hz up to 2kHz for each UCM individually. The best UCM 3 has a 3σ value around 150aF from 200Hz up to 2kHz. In a redesign it should be possible to create a system with 6 matching characteristics in the same region.

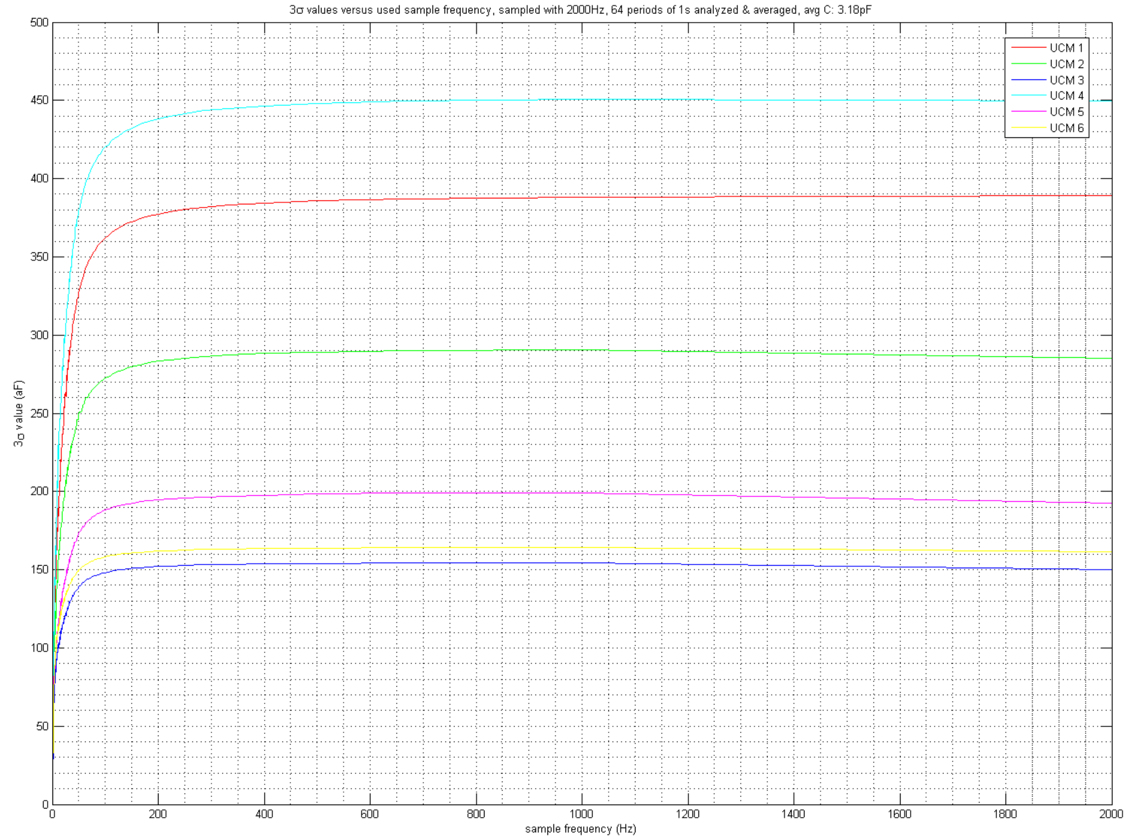


Figure 5.16 Data from Figure 5.13, preprocessed with 40 points average filter

5.4.4 Test conclusion

The resolution of the UCM increases almost logarithmic when sampling the data rate down. When an average filter is used of 10 points (or more), the resolution difference between sampling with 2kHz or 500Hz is almost zero. However, the UCM's are very sensitive for disturbances in their excitation signal used to measure a capacity. A wide spread can occur when all the UCM's sensor wires are guided through the same sub-d connector. Varying the frequency on each UCM can smoothen out differences, but this forces some UCM's to operate outside their optimal settings. Trimming the MS3110 chip on each UCM can give the best & most equal performance, but this has be to done before the chip is soldered onto the UCM PCB. It is still possible to alter the MS3110 settings on the UCM, only verification of the new settings is very difficult, only the excitation frequency can easily be measured. New settings programmed on the UCM will be lost if the power is removed. It is only possible to permanently program the MS3110 settings using the evaluation board.
Also the connector to the outside world has to be replaced by separate BNC connectors for each UCM to use the optimized settings with the least performance hit.

5.5 Test 5: analysis of initial sensor gap width versus capacitive resolution

This test is an analysis of the initial gap width between sensor plates versus capacitive resolution needed assuming a mechanical resolution. Mechanical stroke is fixed (+/-36µm from home position). A desired mechanical resolution of 1nm is assumed.

5.5.1 Test set up

This test is performed in MATLAB only and compared to UCM measurement results from previous tests to estimate the current possibilities of the UCM translated to measurable gap widths.

5.5.2 Measurement procedure

The home position of the sensor is varied between 90µm and 150µm with a few fixed values. The mechanical stroke is controlled by the minimum and maximum stroke of the piezos. Test results showed that all capacitive sensors have a stroke of +/-36µm from home position. With the known conversion factor (Equation 5.7) between capacity and gap width, the minimum and maximum capacity for a number of different home positions can be calculated.

$$d(\mu m) = 486.98 / C(pF) \qquad C(pF) = 486.98 / d(\mu m)$$

Equation 5.7 Conversion between capacity and gap width

Calculating the difference between 2 following values with a fixed mechanical resolution provides the difference in Farad's which has to be detected to obtain the calculated mechanical resolution. This can be seen as a differentiation of Equation 5.7 with the offset of the home position included.

$$\frac{\Delta C(d)}{\Delta d} = \frac{486.98}{d + hp} - \frac{486.98}{d + hp - \Delta d}$$
$$\Delta \text{C(d)} = \text{change in capacity (pF)}$$
$$\Delta \text{d} = \text{resolution required } (\mu\text{m})$$
$$\text{hp} = \text{home position } (\mu\text{m})$$

Equation 5.8 Derivative to determine needed capacitive resolution

For example: a resolution of 1µm is required, this translates to a capacity change when moving from -36µm to -35µm of: 0.164pF (hp of 90µm assumed).

5.5.3 Test results

Figure 5.17 shows the graphical result assuming a needed resolution of 1nm. The horizontal axis shows the sensor position in capacitance for the full range of the mechanical stroke. The vertical axis shows the needed detectable change in picofarad's. So any given gap width can be converted to a capacity on the horizontal axis. The value on the vertical axis corresponding with this horizontal value shows the resolution needed to make a step of 1nm.
In the graphs can be seen that increasing the home position means a decrease in capacitive range as well as a decrease in the capacitive home position. Lower capacities, meaning a greater gap width, require a smaller resolution than higher capacities. Since the capacitive range is also much wider with a lower gap width, it can be concluded that using a lower gap width gives better usage results of the capacitive sensor.
A home position with a gap width of 90µm gives a range of 9.1pF-3.9pF. The smallest resolution needed in the 3.9pF area is 31aF when a mechanical resolution of 1nm is required.
A home position with a gap width of 150µm gives a range of 4.3pF-2.6pF. The smallest resolution needed in the 2.6pF area is 14aF when a mechanical resolution of 1nm is required.

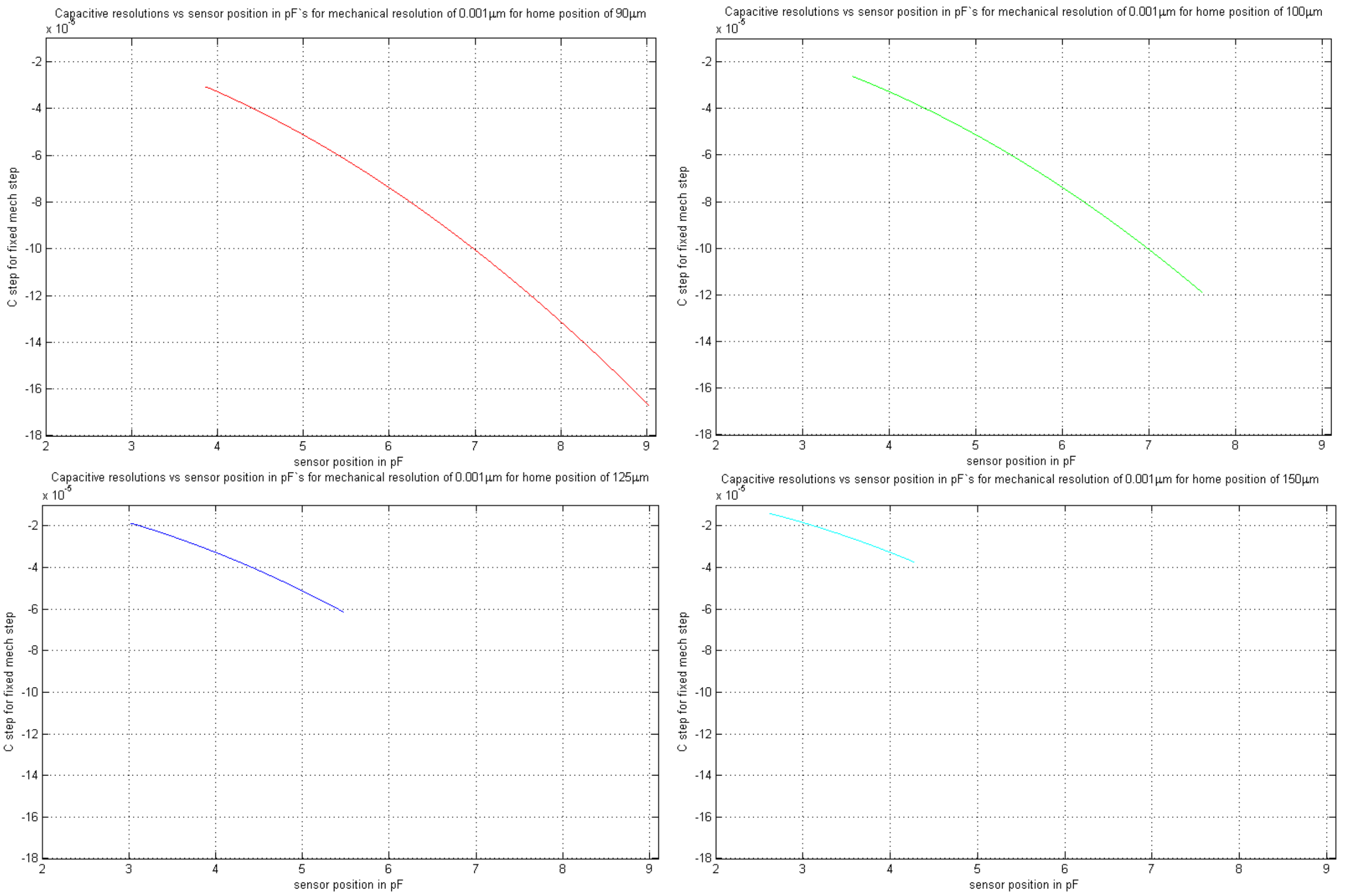


Figure 5.17 Graphs displaying needed capacitive resolution vs sensor position in pF for 4 different sensor home positions

5.5.4 Test conclusion

It could be concluded from ‘Test 3: examine UCM’s performance using shielded reference capacitors’ that staying in a smaller capacity range with the sensors could lead to more accurate position data. Test 5 however shows the other side of the story. The total capacitive range of each sensor is determined by its mechanical stroke. The maximum mechanical stroke is limited in the controller. The capacitive range is therefore determined by the gap width in the home position of the stage. A low gap width gives the greatest capacitive range. Test results are calculated with a desirable mechanical gap width resolution of 1nm. The results state a home position with a gap width of 90µm gives a required resolution of 31aF in the 3.9pF area, which is the lowest capacity in the setting.
A home position of 150µm gives a required resolution of 14aF in the 2.6pF area, which is the lowest capacity using this home position. The required resolution still has to be 31aF in the 3.9pF area.
So the resolution has to be 2.2 times better for the lowest capacity with the different home positions. Test 3 however showed that a capacity of 3.9pF has a resolution of 180aF and a capacity of 2.6pF a resolution of 165aF. The resolution improvement from 3.9pF to 2.6pF is in fact only 1.1. If the UCM can be accurate enough with the gap width of 90µm, it has to be more accurate with a higher gap width to obtain the same mechanical resolution over the total range.
From the other end, the highest capacity, 9.1pF for 150µm, requires a resolution of 167aF, which is 5.4 times greater than the resolution needed at 3.9pF. Test 3 showed that the resolution at 9.1pF is only 1.6 times greater then at 3.9pF.
Hence the ideal mechanical home position of the sensor should be a low gap width, or in electrical terms, a high capacity. The initial capacity minus the capacity needed for the maximum mechanical range should still fall within the UCM’s limits (under 11pF). The highest mechanical resolution possible is determined by the resolution measured at the lowest capacity, or the highest gap width.
The test stage highest resolution is estimated using the worst calibrated gap at its lowest capacity (Sensor 5, gap width ≈ 146µm, C_{RES} ≈ 165aF).

$$res(\mu m) = \left| \frac{486.98}{486.98/(146+36)} - \frac{486.98}{486.98/(146+36)\text{-}165e\text{-}6} \right| = 0.0112\mu m = 11nm$$

If all sensors are calibrated to a gap width of 90µm, the highest resolution is estimated to be:

$$res(\mu m) = \left| \frac{486.98}{486.98/(90+36)} - \frac{486.98}{486.98/(90+36)\text{-}180e\text{-}6} \right| = 0.0059\mu m = 6nm$$

Calibrating all the sensors using 6 UCM’s identical in performance can give an improvement factor of almost 2.

6 REDESIGN INVESTIGATION UCM

Qualifying the UCM with the PCS and the ultra stable reference capacitors has led to some conclusions regarding the limits of the controlled stage and the performance improvement possibilities of the PCS and UCM.
Changes in the controller require an extensive knowledge of control theory and these changes will have the most benefits for a more dynamic use of the stage. The UCM can still be improved in its schematic layout and print layout. Most changes in the case will work best if the UCM itself is also optimized. The choice was made to create a new UCM first, since most performance win is expected here and my knowledge in this area is much more extent than in control theory area.
This chapter includes the pre-redesign investigation of the new UCM. The new UCM will be called UCM+. UCM refers to the first UCM prototype used in the previous chapters. The UCM and available reference data are analyzed and improvements and changes are formulated.

6.1 Ultra stable reference capacitors

In order to test any new or old UCM, a better reference capacity is needed which is ultra-stable so that any noise observed on data is not due to bad reference capacitors. A metal case is created with 10 fixed capacitors inside, each leg of a capacitor soldered directly onto a BNC connector. One of the capacities in the following table can then be connected to any UCM input with minimal noise coupling.
The following capacitors are built inside a metal (aluminum) casing with mini BNC connectors.

Table 6.1 Farnell list used reference capacitors

Farnell code	Supplier	Description
1264864	CORNELL DUBILIER	CD15CD(2.2)DO3F - CAPACITOR, 2.2PF, 500V
1264865	CORNELL DUBILIER	CD15CD(2.2)DO3F - CAPACITOR, 3.3PF, 500V
1264866	CORNELL DUBILIER	CD15CD(2.2)DO3F - CAPACITOR, 4.7PF, 500V
1264867	CORNELL DUBILIER	CD15CD(2.2)DO3F - CAPACITOR, 6,8PF, 500V
1264868	CORNELL DUBILIER	CD15CD(2.2)DO3F - CAPACITOR, 10PF, 500V

All capacitors used are silver mica capacitor types which are very stable and have almost no temperature drift (50ppm/°C typical). Inside the case each capacitor is also shielded from each other by aluminum plates connected to the case. The figure below shows the realization of the shielded reference box

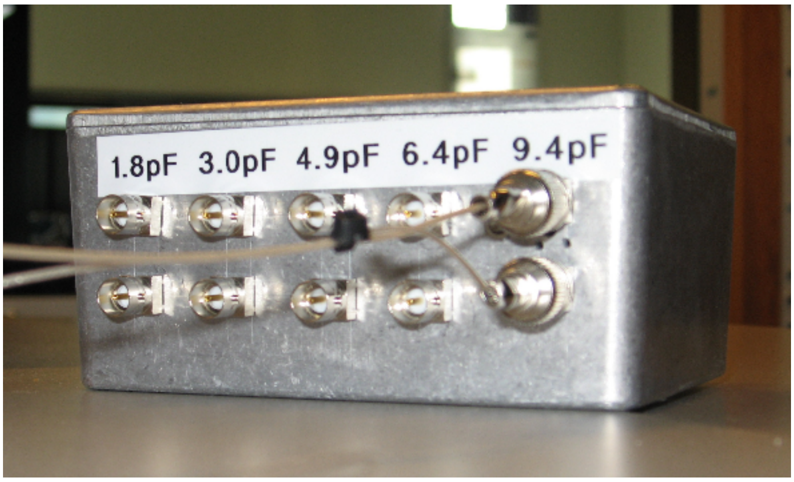


Figure 6.1 Ultra stable fixed reference capacitors inside shielded box

6.2 Redesign specifications

The previous design of the UCM with its tests led to a few clear constraints in order to create the capacitive measurement system once designed.
The original idea was to create a capacity measuring device with a range of 0-10pF and a dynamic range of 10^5, resulting in a resolution of 100aF. However, tests in chapter 5 showed that the obtainable resolution depends on the capacity measured. Lower capacities might be measured with this resolution, high capacities not, but high capacities prove to have much higher mechanical resolution. Since the UCM is designed to measure capacities, all design specifications will be given in Farad's. The previously mentioned resolution might therefore be possible, but probably not in the full range.

In order to obtain the resolution, the bandwidth of the MS3110 (capacity to voltage converter) has to be limited to 500Hz [1]. The used ADC, the ADS1255, can meet the specifications, 16.6 noise free bits [1], according to the datasheet, even on its highest conversion rate 30kHz. The speed however is limited by the CAN bus which is used to transport all data. Only 12ksamples/s can be transported with a Baudrate of 1Mbd [2], leaving a maximum sample rate of 2kHz when 6 UCM+ PCB's are used. If only one UCM+ were to be used in a system, it could sample with 12kHz, etc. However, since the ADC can only be set to sample continuously in certain factors of 30kHz, the maximum sample frequency for 1 UCM+ is limited to 7.5kHz. Tests done with 6 UCM PCB's with a fixed capacitor soldered to their input pads, showed that it was possible to obtain a 100aF standard deviation when sampling with 2000Hz and using a running average filter of 40 samples. The 100aF of the UCM+ should correspond with a 3σ value (three times the standard deviation), preferably without any filtering, since this introduces unwanted phase shift.

So in short the requirements for the UCM+ are:
- Range : 0-10pF
- Resolution : 100aF (@ sample frequency = 2kHz)
- Dynamic range : 10^5 (@ sample frequency = 2kHz)
- Noise free resolution : 16.6bits (@ sample frequency = 2kHz)
- MS3110 bandwidth : 500Hz
- ADC sample speed : 2.5Hz – 7.5kHz (Depending on UCM+ and ADC configuration)
- Short term stability : 200aF/hr
- Long term stability : 400aF/day
- Absolute accuracy : +/- 1%
- Temperature stability : +/- 0.1˚C/hr

The current UCM houses 2 microcontrollers. One is responsible for communication and one for reading out the ADC and filtering the data. It might be possible to reduce the microcontroller count to one, since both µc's are now not doing anything most of the time

6.2.1 MS3110 Specifications

Extensive research has been done [7] regarding the settings and performance of the MS3110. Although the specifications state that each MS3110 has to be trimmed with its own settings, it has not been implemented on the UCM_E_01_001a. Now each MS3110 is programmed the same register settings in its volatile registers at boot-up. In order to get the most out of the chip, each MS3110 has to be trimmed individually in the evaluation board socket. The trimmed register values then are programmed in the EEPROM. The MS3110 copies the values in its EEPROM to volatile registers at power up, these volatile registers can be overwritten, but they should be read first to read the values of the trimmed registers.
The chip can be soldered onto the UCM+ and when a read/write interface is implemented; the software can read the trimmed values first and then alter some other settings if the user wishes to change the bandwidth for example.

The settings for operation are as follows (the MS3110 is programmed in the ZIF socket of the evaluation board):
- **V2P25** (Pin 2) should be trimmed to 2.25V ±10mV
- Reference current (between Pin 3 and ground) should be trimmed to 10µA ±2µA
- Oscillator frequency (Pin 4 or 6) should be trimmed to 100kHz ± 5kHz
- **Off** has to be trimmed (output buffer offset)
- **B** can also be trimmed (buffer gain correction), but with great care!
- **Vref** should be set to 2.25V
- **CS1** has to be set to 5.263pF
- **CS2** has to be set to 0.266pF
- **CF** has to be set to 14.668pF
- **GAIN** has to be set to 2

After each individual chip is trimmed, it can be soldered to a new UCM+ PCB. There it is possible to read out the registers and write other values if needed. It is mentioned in [7] that it is not possible to program the EPROM on the MS3110, but a quick test showed that the chip remembered its new register values after an EPROM update followed by a total power removal. The MS3110's output goes blank when the link with the PC is disconnected, but this is probably due to an uncontrolled reset line.

Two mini BNC connectors provide a shielded signal line to an external capacity. All traces regarding the capacity measurement will be as short as possible. The external components will be the same as in the UCM_E_01_0011a design, only the WRT pin of the chip also has to be connected to the LPC2129.

Appendix B: MS3110 trimming procedure contains step by step instructions to trim the MS3110 properly.

An elbow BNC connector could be placed on the edge of the PCB with 2 nuts so it the connector is directly accessible from outside the case. The shield of the connector however connect make any connection to the grounded case, since voltage differences between these two levels exist. Connecting them would add noise to the analog ground plane or between the ground planes of adjacent UCM+'s.

On Farnell for example (order number 1111298), a right angle 75ohm PCB jack with a polypropylene insulation could be used. No extra cables or connectors are needed to connect the PCB to the case for the MS3110 input connection.

6.2.2 ADS1255 Specifications

The same ADC with the same components will be used. The ADC always samples with 30kHz, if a lower data rate is selected, the ADC averages a number of measurements, increasing the effective number of bits. The microcontroller could also read the ADC with 30kHz and filter the samples itself, but by using a lower data rate the microcontroller has more time to apply other filters or send the data. If the data rate is set to 2kHz, the averager inside the ADC uses 15 ADC values to create one output value. 2kHz is still fast enough, since the MS3110 output's bandwidth is limited to by a 2nd order low pass filter to 500Hz. The notch filter created by the averager has the first -3dB point at 878Hz when using a data rate of 2kHz.
A higher data rate could be used also, but this would lead to a drop of performance also, but the user could decide that higher data rate is more important than resolution.

The settings for the ADS1255 remain about the same. The ADC is first sent a reset command setting all registers to their default values. The ADC can then be configured with a write command followed by the following values:

Table 6.2 Register values ADS1255

Name	Address	Value	Description
STATUS:	0x00	0x02	Sets MSB to be sent first, auto-calibration off, buffer on
MUX:	0x01	0x01	Positive channel AIN0, negative channel AIN1
ADCON:	0x02	0x01	Turns output clock and sensor detection off, sets PGA to 2
DRATE:	0x03	0xB0	Sets output data-rate to 2000 samples per second
GPIO:	0x04	0x00	Digital IO not used on design

After these commands a self-calibrating instruction is sent to optimize ADC performance. When more UCM+'s are used in one configuration, the synchronize command can be used to synchronize the ADC's on different UCM+'s.

6.3 Printed circuit board changes/additions

All changes and references used refer to the designed UCM schematic with code UCM_E_01_0011a.130. A small version of this schematic can be found in Appendix E: UCM_01_0011a Schematic.

6.3.1 PCB schematic changes/additions

6.3.1.1 MS3110 schematic update

Most components of the MS3110 will be copied; a few changes will be made:
- C25, C1: change to ceramic type, lower ESR, less space needed, filter high frequencies better
- J12: connector for usage PCB as voltage meter connect to voltage output of MS3110 with solder jumper
- The WRT pin of the MS3110 has to be connected to the LPC2129 in order to read the registers
- Straight-through mini BNC connectors can be used to connect MS3110 input to capacitive sensor
- Filter digital I/O lines towards MS3110 to attenuate digital noise coupled into MS3110

6.3.1.2 Component removal/replacement list

The following components can be removed from the current schematic:
- Slave microcontroller U15 with all its components
- Remove 16MHz oscillator (U22) with all its components. Replace with 12MHz crystal with 2 22pF capacitors
- Replace 4 HDR1X2 connectors by one (J1, J2, J3, J28)
- Remove unneeded COM-port pins (keep header implementation)
- Remove CAN jumpers J7, J8, J9

6.3.1.3 Component addition list

The following components should be added to the current schematic (previous mentioned components are not included in the list):

- Selectable UCM number by using jumper code on three I/O lines of LPC2129. Use pull-down resistors with jumper to 3.3V.
- Selectable UCM sample rate by using jumper code on five I/O lines of LPC2129. Use pull-down resistors with jumper to 3.3V.
- Add LED's to lay-out to indicate data transmission. Connect to LPC I/O with transistor.
-

6.3.2 PCB lay-out changes/additions

6.3.2.1 Ground plane & layer configuration

The original plane contains two separate ground planes. The idea is that a digital and an analog ground plane both are not connected together, but still have a voltage difference of 0 V. This can however never be the case, since sooner or later both grounds will have to be connected together, by then the impedance of the used cabling, connectors, etc, will already have created a voltage difference, perhaps from a few mV even. This is a significant difference when trying to measure 60µV differences on an analog signal. Both grounds have to connected with the lowest impedance as possible, this can be done by creating one large ground plane for both digital and analog components or a wide connection at one point. A careful layout has to be made which places all the analog and digital parts together. Especially noisy currents from digital lines have to be placed far from sensitive analog lines. All currents can then return on a path opposite of the signal line since this provides the lowest impedance for the current.
Noisy currents, when components are carefully placed, will therefore have a minimal influence on the ground plane below the analog parts.
A separate region could also be created and the planes could be connected under the ADC or at the power supply input to keep some more noise out, but a trace should never go over a split in the ground plane. Currents always have to make the smallest loop possible in order to minimize interference. So a good partition layout is the best solution. All the digital components with their traces remain in the digital section and the same goes for the analog parts.

When using a 4 layer PCB, the following layer configuration can be used:

- Ground plane & short traces
- Signals & Power traces
- Signals & Power traces
- Ground plane

Via's can be placed around the edge of the board to provide a cage of Faraday which eliminates some radiated and received noise. Via's from layer 1 to layer 4 can also be placed between the analog and digital section to improve each other's shielding. Separate power IC's can be used for the analog and digital section so the current paths can be better predicted. The analog section only requires a 5V and 2.5V regulator. A few wide traces will deliver the power to the needed components with a few decoupling capacitors. The digital section requires a 5V, 3.3V and a 1.8V regulator.
One power source can provide at least 7.5V to all the regulators inputs. The input of each regulator should include a ferrite bead connected by a capacitor on each side to minimize noise injection in each direction. Also noisy digital IC's should have a ferrite bead in their power trace with a few decoupling capacitors placed as close to the IC as possible.
Decoupling capacitors should mainly be of the multi-layer ceramic type, preferably X7R, wherever possible, unless capacitor size is too big to use a X7R capacitor. Capacitor sizes lower then 10µF can be ceramic ones when using an SMD0805 case.

6.4 Updated software requirements

Since both LPC's will be replaced by one LPC, firmware has to be rewritten. It should essentially be a combination of the slave & master firmware without the parallel protocol implemented [1]. A few additions will be made also:

- External jumper settings will be read at start-up to determine its UCM+ number and sample rate
- At boot-up, all UCM+ PCB's will communicate over the CAN bus to determine the number of present UCM+'s and maximum sample frequency. Duplicate UCM+ numbers will have to be detected and forwarded to the user.
- Watchdog will be used to soft reset the UCM+ if code hangs unexpected.
- Operate LED to indicate system status
- A command interface will be implemented processing various CAN commands

Figure 6.3 shows a simplified flowchart of the firmware for the UCM+. Only one microcontroller is implemented on each UCM+, so the same flowchart can be used for each UCM+. Two LED's are implemented on each UCM+ controlled by LPC I/O's. A LED change is shown next to the current state of the firmware in Figure 6.3.
Since the interrupt service routines also got more complex with the addition of CAN commands, a simplified flowchart of the CAN interrupt routines when data is received or transmitted is shown in Figure 6.2.

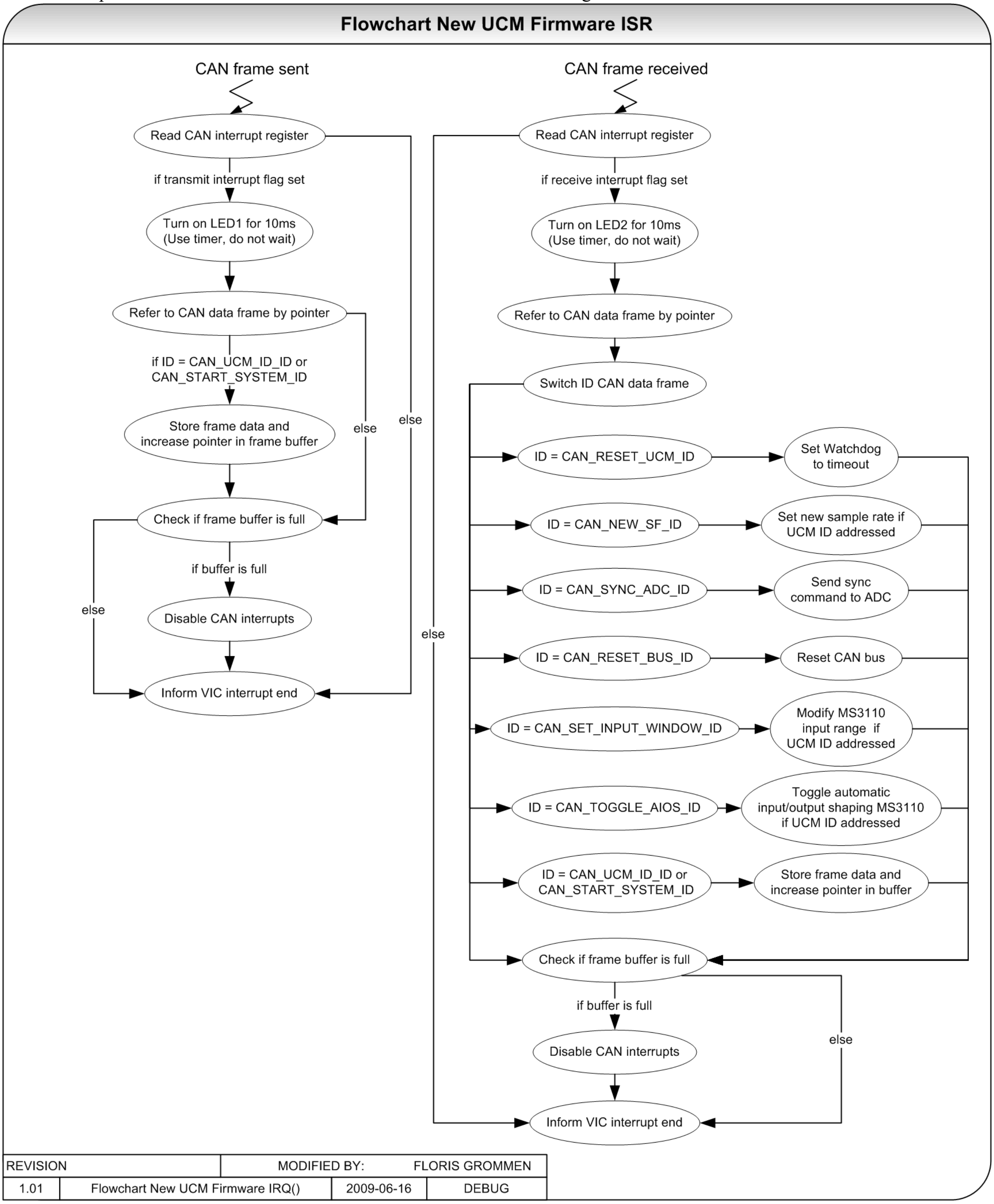


Figure 6.2 Flowchart of new UCM+ firmware, CAN interrupt service routines

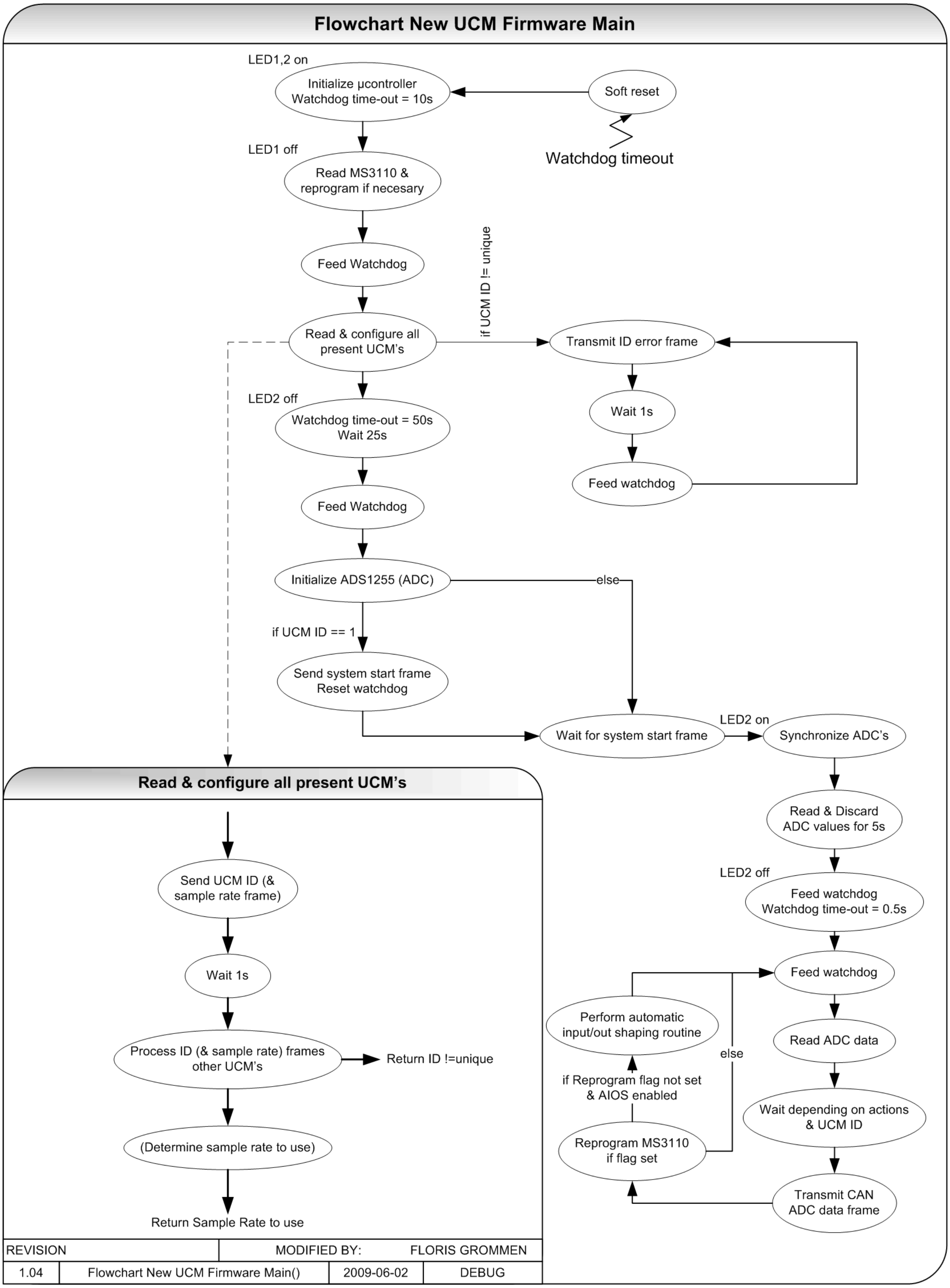


Figure 6.3 Flowchart of new UCM+ firmware, main function

6.5 Conversion mathematics

6.5.1 MS3110 and ADS1255 (ADC) conversion relation

This sub-chapter describes the mathematical relationship between the input of the MS3110 and the output which is then converted by the ADS1255 in a digital code and converted to a matching value for the MS3110's input.
The following table shows the relation in transporting the capacitive input data between the main components:

Table 6.3 Data type relation between main components UCM+

Signal from	Input signal of →	Component	Output signal of ←	Signal to
MS3110	100kHz square wave	Capacitive sensor	Current ≈ C of sensor	MS3110
Capacitive sensor	Current ≈ C of sensor	MS3110 (C-VC)	Analog V ≈ C of sensor	ADS1255
ADS1255	24bits code U_{IN} ADC	LPC2129 (µcontroller)	24bits code C_{SENSOR}	End controller
End controller	Undefined	End user		

Each component has an output with a restricted range or value:

- MS3110 output: Datasheet defines voltage between 0.5V and 4V, measurements show that actually values between 0-5V occur. Probably 0.5-4V most accurate data.
- ADS1255 output: Digital bipolar 24bits code for analog input voltage. MS3110 output is subtracted with 2.5V reference to use full span input of ADS1255.
- LPC2129 output: CAN frame with 24bits code representing capacity of input sensor or capacity in attofarads ($Cx10^{-18}F$). Code restricted from 0pF to 11pF.

The MS3110 explains the relationship between input and output with the following formula:

$$U_{OUT} = GAIN \times V2P25 \times 1.14 \times ((CS2IN + CS2) - (CS1IN + CS1)) / CF + VREF$$

Equation 6.1 MS3110 conversion from input to output

GAIN can be 2 or 4, but is always set to 2
V2P25 equals the trimmed 2.25VDC reference voltage
CS2IN is the capacity connected at the input of the UCM+
CS2 and CS1 are configured by the LPC and used as on offset for the capacitive input signal
CS1IN is always 0 since this input is not connected
CF determines the sense capacitance range
VREF can 0.5VDC or 2.25VDC, but is always set to 2.25VDC

With this information the relation can be rewritten to:

$$U_{OUT} = 2 \times 2.25 \times 1.14 \times (CS2IN + CS2 - CS1) / CF + 2.25 = 5.13(CS2IN + CS2 - CS1) / CF + 2.25$$

Equation 6.2 Simplified MS3110 conversion from input to output using UCM+ settings

The relation between ADC's input and output is:

$$Code = (U_{IN} - 2.5) \times \frac{2^{24}}{5}$$

Equation 6.3 Conversion U_{OUT} MS3110 to ADC code (U_{OUT} MS3110 = U_{IN} ADC)

Code is the 24-bits code. This code is converted from a bipolar to a unipolar code by inverting the most significant bit. This way, when calculating from Code back to Capacitance, the -2.5V offset can be omitted.
With the equations above, one equation can be written to convert an ADC code back to a capacitance:

$$Code = U_{OUT(MS3110)} \times \frac{2^{24}}{5}$$

$$Code = \left[5.13(CS2IN + CS2 - CS1) / CF + 2.25\right] \times \frac{2^{24}}{5}$$

$$Code \times \frac{5}{2^{24}} - 2.25 = 5.13(CS2IN + CS2 - CS1) / CF$$

$$\frac{(Code \times \frac{5}{2^{24}} - 2.25) \times CF}{5.13} = CS2IN + CS2 - CS1$$
$$Code \times CF \times \frac{5}{2^{24}} / 5.13 - 2.25 \times CF / 5.13 + CS1 - CS2 = CS2IN$$

Equation 6.4 Conversion back from ADC code to input capacity

This formula is used to convert the ADC code to a digital code representing capacitance. Since the output is in aF, CF, CS1 and CS2 also have to be specified in aF.

6.5.2 MS3110 input tracking & focusing mathematics

In order to improve the resolution of the MS3110, an attempt is made by varying the capacitance input range in order to focus on a smaller capacitive range. This way the same output voltage swing of the MS3110 is used for a smaller range, increasing the number of bits that correspond with one Pico farad. An algorithm is used which automatically expands or shrinks the measurement range depending on input signal dynamics.
The input range is determined by various MS3110 settings, but only 3 settings will be adjusted in the algorithm CF, CS1 and CS2. They can be trimmed in steps of 19fF; all the values have to be rounded down in 19fF steps. CS2 is also always set to 0, only at boot-up it is set to the old default value of 0.266pF.
CS1 is a capacitive offset which is deducted from the input. To provide optimal focusing, CS1 should be set to be in the middle of the capacitance sense range. In formula:

$$CS1 = \frac{C_{HIGH} + C_{LOW}}{2}$$

Equation 6.5 Offset register CS1 calculation

CF can be calculated by assuming the high capacitive range corresponds with $4V_{OUT}$ of the MS3110. Rewriting the MS3110 output equation gives a solution for CF:

$$U_{OUT} = 5.13 \times (CS2IN + CS2 - CS1) / CF + 2.25$$
$$CF \times (4 - 2.25) = 5.13 \times (C_{HIGH} - CS1)$$
$$CF = \frac{5.13}{1.75} \times (C_{HIGH} - CS1) = \frac{5.13}{1.75} \times (C_{HIGH} - \frac{C_{HIGH} + C_{LOW}}{2})$$
$$CF = \frac{5.13}{1.75} \times (C_{HIGH} - \frac{C_{HIGH}}{2} - \frac{C_{LOW}}{2}) = \frac{5.13}{1.75} \times (\frac{C_{HIGH} - C_{LOW}}{2})$$

Equation 6.6 Gain register CF calculation

7 REALIZED REDESIGN

7.1 MULTISIM schematic

The figures in this chapter show the redesigned schematic divided in separate pages. The first redesign had 4 pages; the final realized redesign had 5 pages due to an increase in part complexity between MS3110 and LPC2129 communication. Under each figure, a short description of the changes from schematic *UCM_E_01_0011a.130.ms10* to *UCM_E_01_002.130.ms10* and newer versions is listed. The newest version is listed on top.

7.1.1 Microcontroller section with JTAG & CAN

7.1.1.1 Revision 1.1

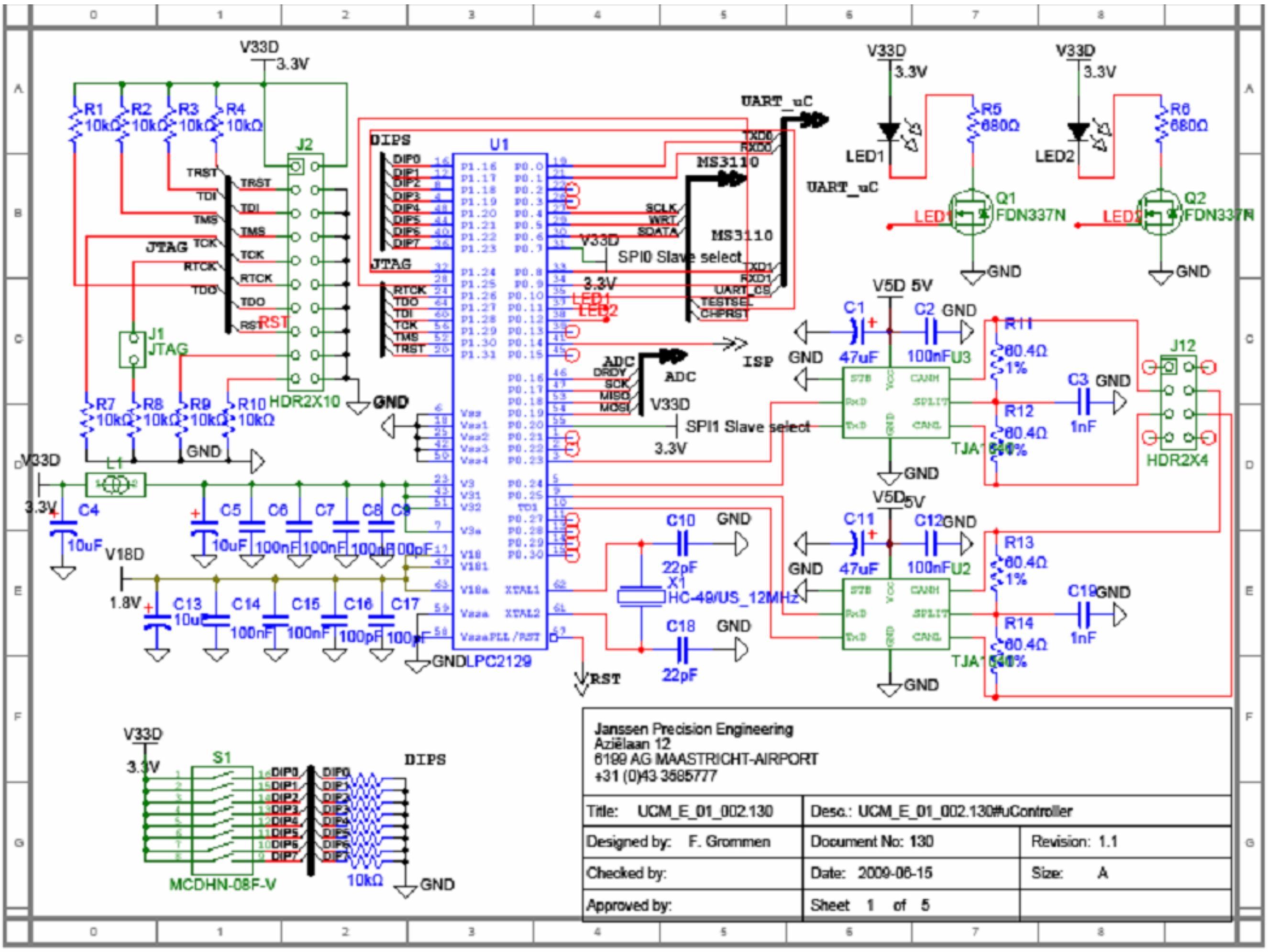


Figure 7.1 Microcontroller section with CAN communication Revision 1.1

Changes Revision 1.1:

- Decreased resistor values next to dips (1MΩ to 10kΩ). Leakage current created high voltage when dip set to low
- Added 1 more signal LED
- Updated pins communicating with MS3110. Communication now by optocouplers and SPI bus 0 can be used to communicate.
- Addition of 100pF capacitors to microcontroller power supply lines.

7.1.1.2 Revision 1.0

Changes Revision 1.0:

- The UCM design had 2 microcontrollers, now only 1 is used, since data transmission now occurs on the CAN bus.
- The 16MHz oscillator used to drive the clock input for 2 µcontrollers is replaced by a 12MHz crystal. This way the µcontroller can work at its optimum speed.
- A ferrite bead has been added to the 3.3V power input of the µcontroller to suppress noise on the power lines going in and out of the µcontroller.
- 8 Dip switches are added to the design to specify an UCM+ ID and sample rate.
- A LED is added which can be used to provide the user with visual status information.
- A few extra I/O lines of the µcontroller are used to communicate with the MS3110 to give a more flexible use of it.
- Various jumpers have been removed in the CAN part.

7.1.2 Digital and analogue power supply section

7.1.2.1 Revision 1.1

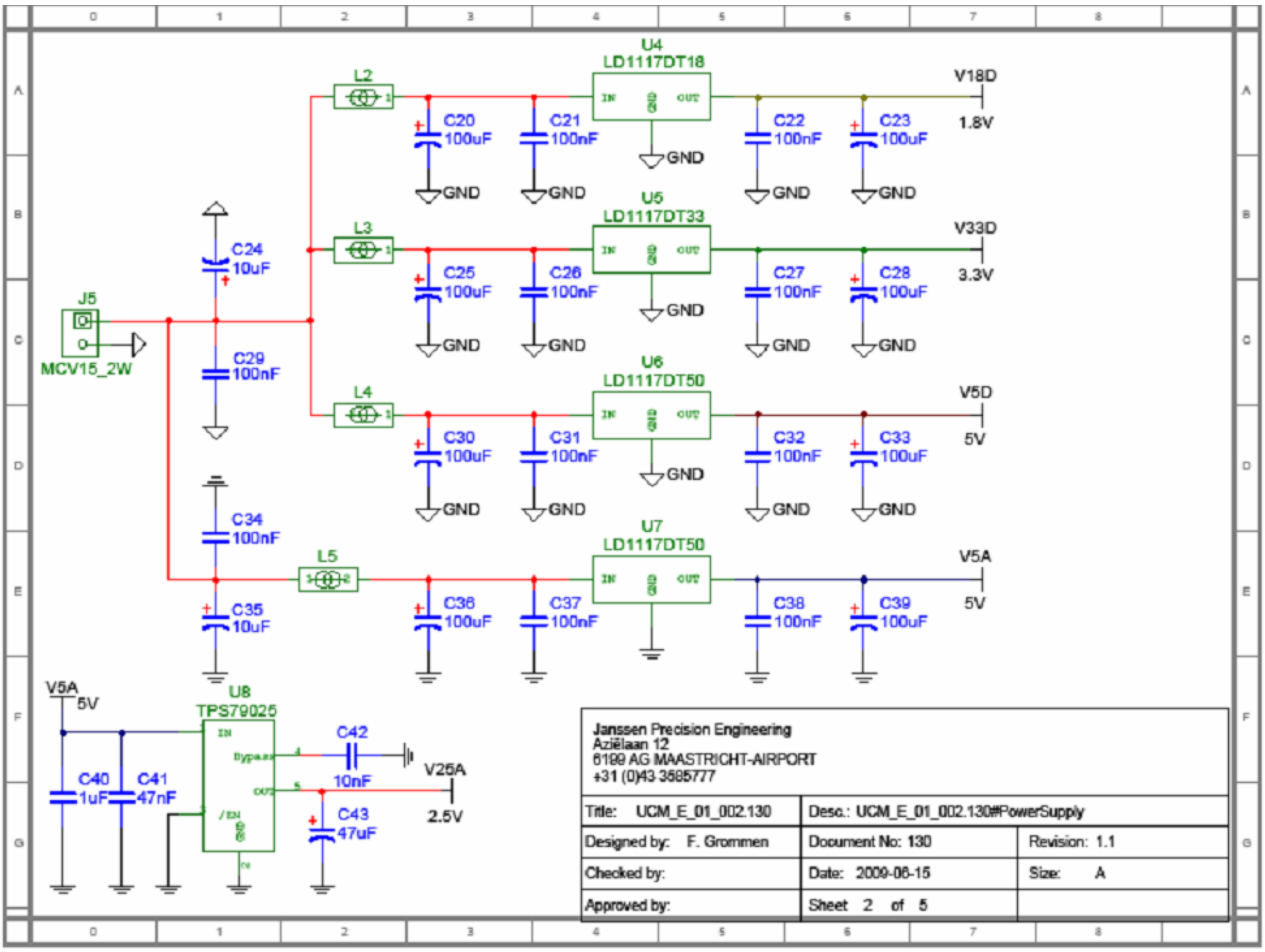


Figure 7.2 Power supply section Revision 1.1

Change Revision 1.0:

- 2 Ferrite beads replaced by 4 ferrite beads, 1 for each power regulator to minimize bead current saturation

7.1.2.2 Revision 1.0

Changes Revision 1.0:
- One connector is used to connect a 6.5-9V power supply.
- The digital and analogue power supply generators are separated by RLC-filters in both directions (analogue<->digital as well as power supply lines in<->out). The RL's are ferrite beads with high impedance (typ. 0.6Ω @ DC, 2250Ω @ 100MHz) at higher frequencies.
- Analogue and digital ground plane are connected to each other to assure the lowest impedance between analogue and digital ground plane. Careful layout of the PCB has to maintain a quiet analogue ground plane. *3.3.2.1 Ground plane & layer configuration* provides more information on this topic.

7.1.3 UART communication with PC section

7.1.3.1 Revision 1.1

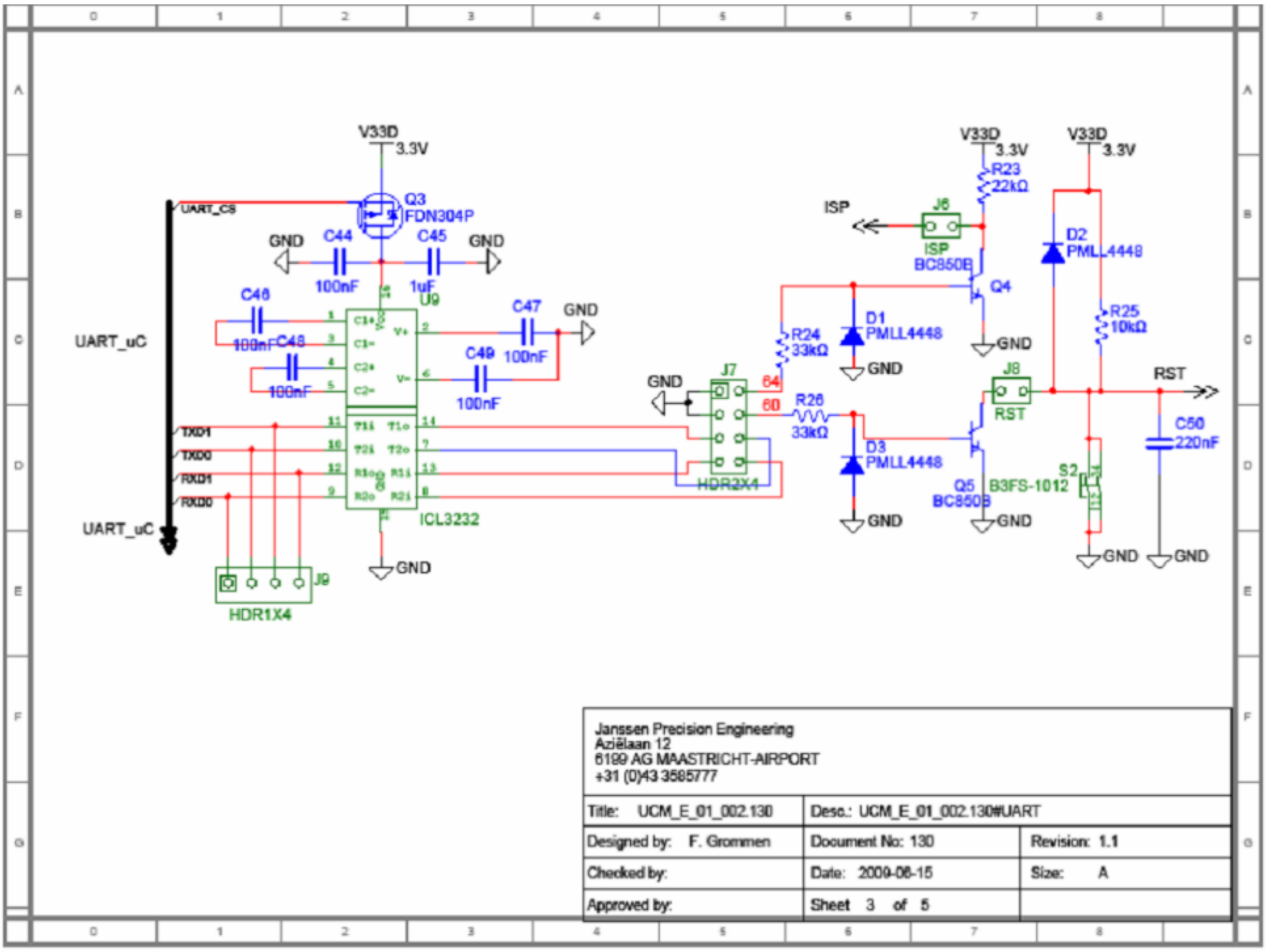


Figure 7.3 UART communication section Revision 1.1

Changes Revision 1.1:
- Q3 added to disable RS232 transceiver. Transceiver can cause noise spikes on ground due to switching behavior.
- J9 added to use additional IO when needed instead of COM channel
- C50 in reset circuitry increased to 220nF. Reset pulse else shorter then time needed for power supply to reach end value (Bad reset LPC at power on).

7.1.3.2 Revision 1.0

Changes Revision 1.0:

- Only a header is used which can be used to reprogram the µcontroller in case JTAG communication has been disabled. It can also be used to transmit data between µcontroller & PC in case some extra debug information is desirable.
- Only a few component changes are implemented, but their function is the same. Layout is identical to prototype layout.

7.1.4 Analogue section: MS3110 with ADC and voltage reference

7.1.4.1 Revision 1.1

7.1.4.1.1 Global schematic MS3110 with ADC and voltage reference

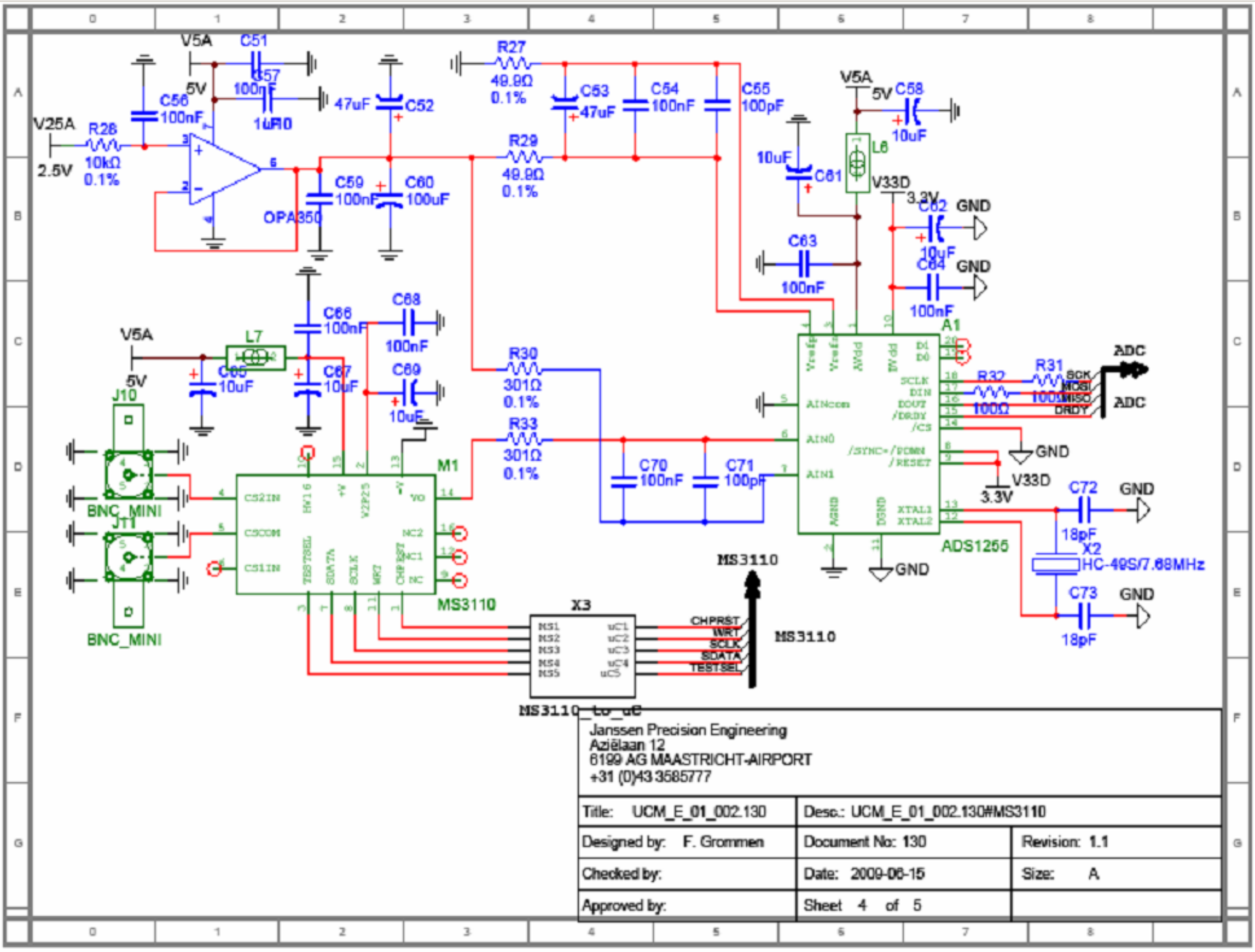


Figure 7.4 MS3110 with ADC section Revision 1.1

Changes Revision 1.1:

- Communication between MS3110 and LPC2129 updated. Now optocouplers are used. Sub-circuit used due to increased part count.

7.1.4.1.2 Communication schematic MS3110 with LPC2129

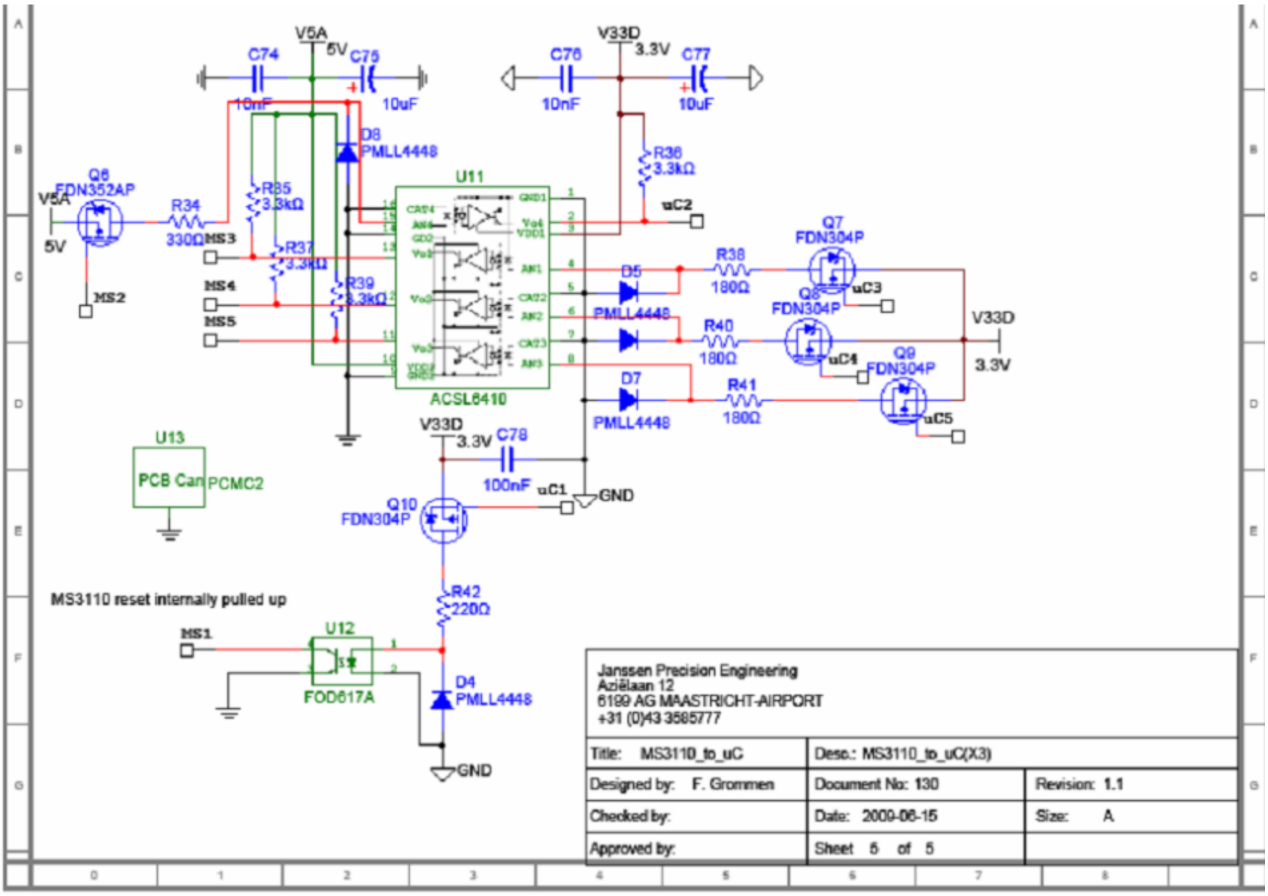


Figure 7.5 Communication section between MS3110 and LPC2129 Revision 1.1

Changes Revision 1.1:

- SPI like communication with high speed 3-1 optocoupler.
- Diodes added to increase switch speed.
- P-channel MOSFET's used to toggle LED's inside optocoupler.
- Q6 different type, since WRT line coming out of MS3110 has 4V high, but supply voltage is 5V. Higher U_{GS-TH} is needed.
- U12 is basic optocoupler, only needed to pull MS3110 reset line to ground. Reset line is internally pulled up to 5V.
- U13 added to mount a shielding case over MS3110 in printed circuit board design.
- Revision 1.0 omitted since design was faulty.

7.1.4.2 Revision 1.0

Changes Revision 1.0:

- Voltage reference is unaltered with only some component changes. Paragraph 7.2 Component changes gives more information regarding the new components. Reference circuit implemented as shown in [15].
- Ferrite beads have been added to power supply input of MS3110 and ADC. This to minimize the noise going in and out of these components. Especially the MS3110, which has an internal connection between digital and analogue power, could leave some noise on the analogue power net.
- A new level converter IC is used to communicate between MS3110 and µcontroller. The µcontroller can now reset the chip, let the MS3110 load its configuration from EEPROM or volatile registers, program the volatile registers as well as read them, giving the µcontroller total flexibility in operating the MS3110.
  The level converter can also be disabled, so there is now unwanted noise coupled into the MS3110 by the digital lines. In this case, all digital input of the MS3110 except for the reset pin is tied to ground.
- The reset pin of MS3110 is operated by an open drain output of the µcontroller, created by Q4. The reset pin is internally pulled up.

7.2 Component changes

As well as schematic changes, most changes are made in the used components. Some components are no longer available or the used components were overrated or underrated for the used application. The list below only contains the most important changes. Appendix A: contains a list of all the used components in the revised schematic, but not any external components needed.

Changes:

- 10µ tantalum capacitors now case A instead of D giving lower ESL and more effective placement on PCB (C's can be placed closer to IC which needs decoupling). Same applies to 47µ capacitors. They have a C case package now.
- Tantalum capacitors are selected with a lower maximum voltage rating. Devices rated above 10VDC have a recommended derating of 20%, so a tantalum capacitor with a rating of 16VDC can be used before the voltage regulators and capacitors with a rating of at least 10VDC are safe to use in the other voltage nets.
- The resistors used in the analogue section of the schematic (Figure 7.4), are replaced by thin film type SMD resistors. These resistors have a superior value accuracy and temperature coefficient compared to thick film types. All resistors used have a temperature coefficient of 10ppm/˚C and a value accuracy of 0.1%. All other resistors are thick film. No accuracy is required and they are far cheaper than thin film resistors.

7.3 Realized firmware

The firmware running on UCM+ is the same firmware as shown in the flowcharts in Figure 6.2 and Figure 6.3. The complete source code is not included, but is available upon request. The latest source code can be found in *G:\JPE\Control\UniversalCapacityMeasurementIntegration\WERKdir_SW\03_KEILfiles\FIRMWARE UCM_E_01_002\Version 1.0*.
Appendix D: contains a description how to use the new UCM and how to interact with it using commands sent over CAN.

8 TEST RESULTS UCM+ (UCM_01_002)

8.1 Test 1: UCM+ (UCM_01_002) versus UCM (UCM_01_0011a)

The same test is done as with the old UCM (described in 5.4 Test 4: UCM's performance versus sample frequency). The aluminum box with shielded MICA capacitors inside is used to connect one capacitor to the UCM+. Results are logged real time and processed offline.

8.1.1 Test set up

The UCM+ PCB is connected to a separate microcontroller board (MCB2100) by one CAN bus. The MCB2100 board is connected to the PC using an RS232 to USB cable. With this cable it is possible to create a 375kBd communication link between PC and MCB2100. Various commands can be sent over this link to the MCB2100 which then sends a corresponding command over the CAN bus.
When the UCM+ PCB is running, it sends continuously new samples to the MCB2100 over the CAN link which transmits the samples real time to the PC. Samples can be logged here for offline processing.
The MCB2100 has to be flashed with the contents of project *G:\JPE\Control\UniversalCapacityMeasurementIntegration\WERKdir_SW\03_KEILfiles\FIRMWARE UCM HOST VERSION 2.0\firmware_UCM_host.Uv2*.The aluminum box with the 3.1pF capacitor is connected to the UCM+. The test setup is identical to Figure 5.9, only now the UCM+ is used.

8.1.2 Measurement procedure

If all hardware is connected and powered on, a LABVIEW application can be started to communicate with the MCB2100 and log raw data. A dropdown menu is implemented which lists the available commands. First set the correct sample rate and press write, and then make sure the Log button is pressed to enable on file logging and select *Toggle UCM0 Output* to start sending the data from MCB2100 to PC. When enough results are logged write the same command to stop the logging. The log file, which only contains binary data and an ASCII number for the UCM number, has to be converted to an ASCII file with time reference before it can be processed in MATLAB. The included UCM numbers in the log file are used to check the log file for consistency when converting the log.
The converted log is loaded in a MATLAB script which analyzes the logs in 1s windows by finding the 3σ values in Farads for each window and then averages the values for the number of windows. Data is then sampled down and the same 3σ analysis is performed for the data with lower sample rate (2 following samples become 1 sample, then 3 following samples become 1 sample, and so on. An FFT analysis can also be done to get an idea of the frequency contents of the data. Previous tests could not be analyzed in the frequency domain, since they were not logged real-time. The FFT analysis also shows the SNR in dB.

$$SNR = 10 \times {}^{10}\log \frac{F(0)}{\sqrt{F(1)^2 + F(2)^2 + F(3)^2 + \ldots}}$$

Equation 8.1 Signal-to-noise ratio in dB's

8.1.3 Test results

The first figure shows the 3σ values in attofarads against the used sample frequency from the UCM and UCM+. The new noise level is about 80% of the original level, compared to the best performing UCM (rev UCM_01_0011a).

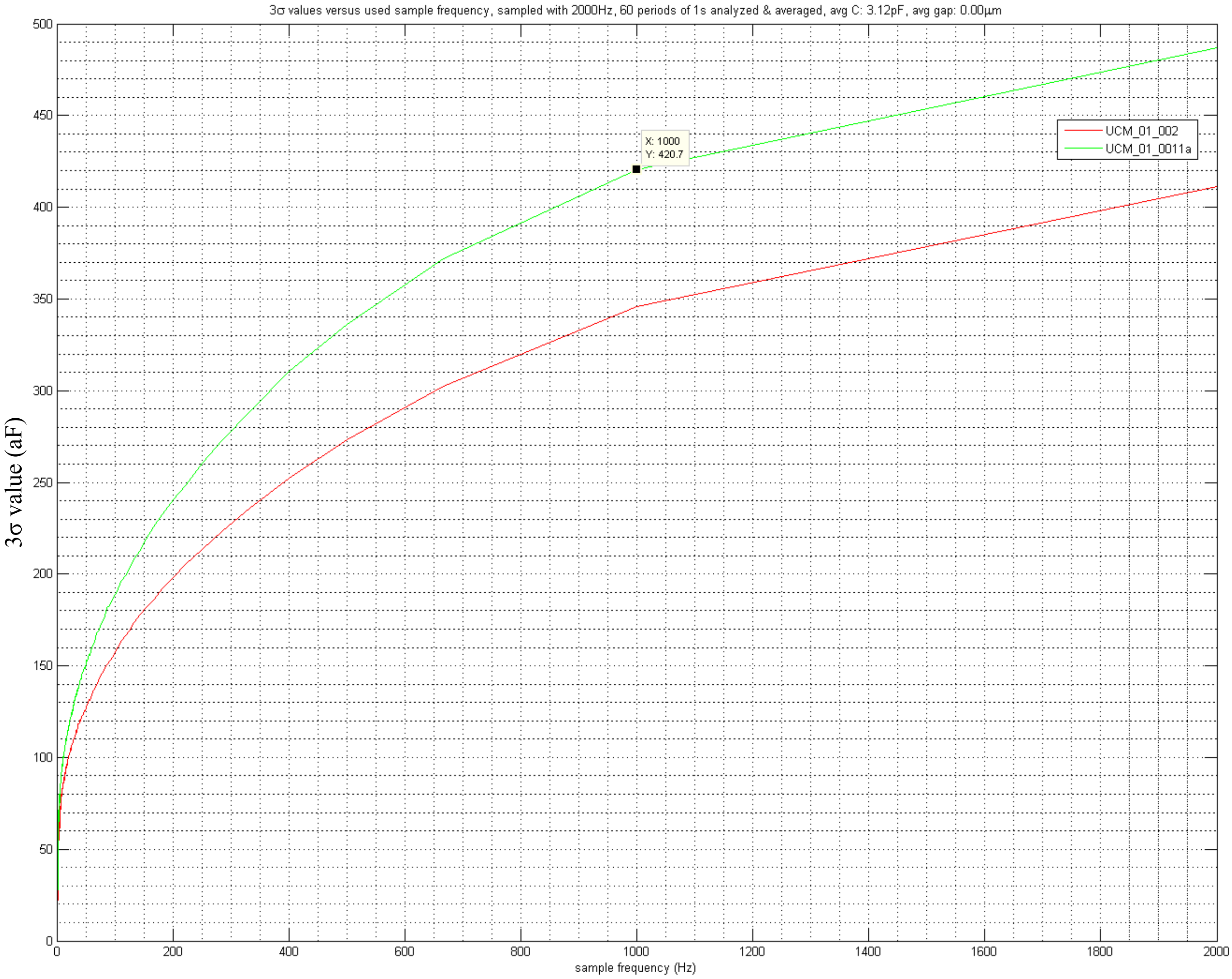
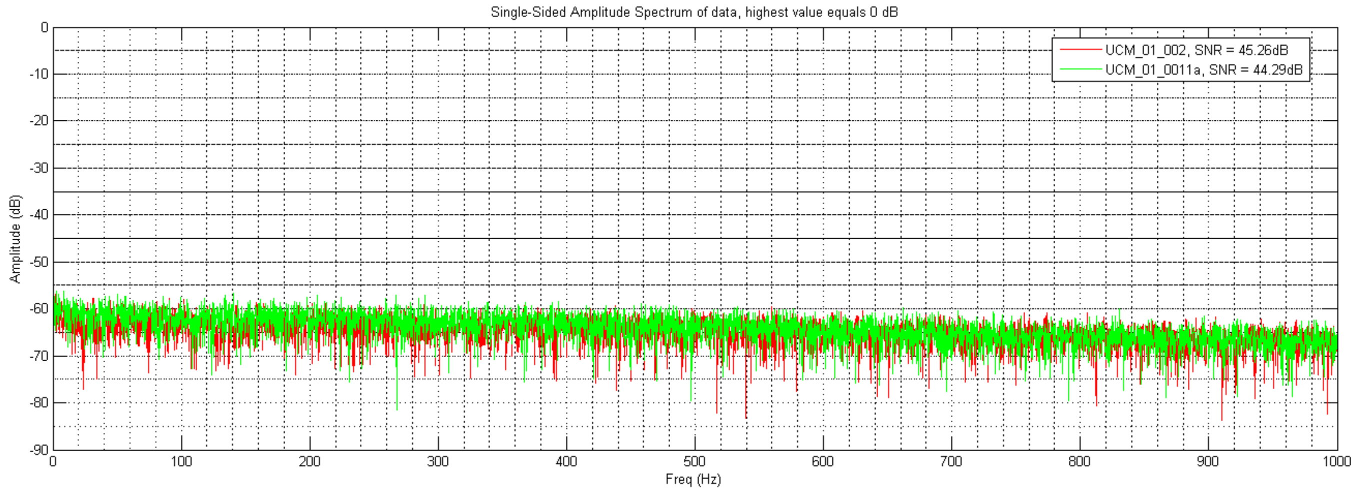


Figure 8.1 UCM versus UCM+, capacitive noise versus used sample frequency

The second image is an FFT plot of the same data. This plot is only created for a sample frequency of 2000Hz. Values are scaled in a way that 0dB equals the highest amplitude, in this case 0Hz. The graph is created by taking the ^{10}log of the FFT coefficients and multiplies them by 10. The amplitude in dB in this graph for each frequency is a measure for the estimated amplitude (in nm) of a signal with frequency f in the analyzed data. The data is moved so only a noise ratio can be expressed for each frequency coefficient. Most frequencies have signal to noise ratio of about 60dB ($1x10^6$). The coefficients of the FFT are always lower than the actual values, due to calculation imperfections.
The UCM+ has slightly less noise, which can easiest be seen by the 1dB SNR improvement (1dB corresponds with a factor of 1.26). The phase graphs of both UCM's show similar patterns between +100 and -100 degrees, mainly. Higher frequencies (>500Hz) do not provide reliable numbers. A more extensive FFT analysis should be performed to display the phase characteristic more accurately.



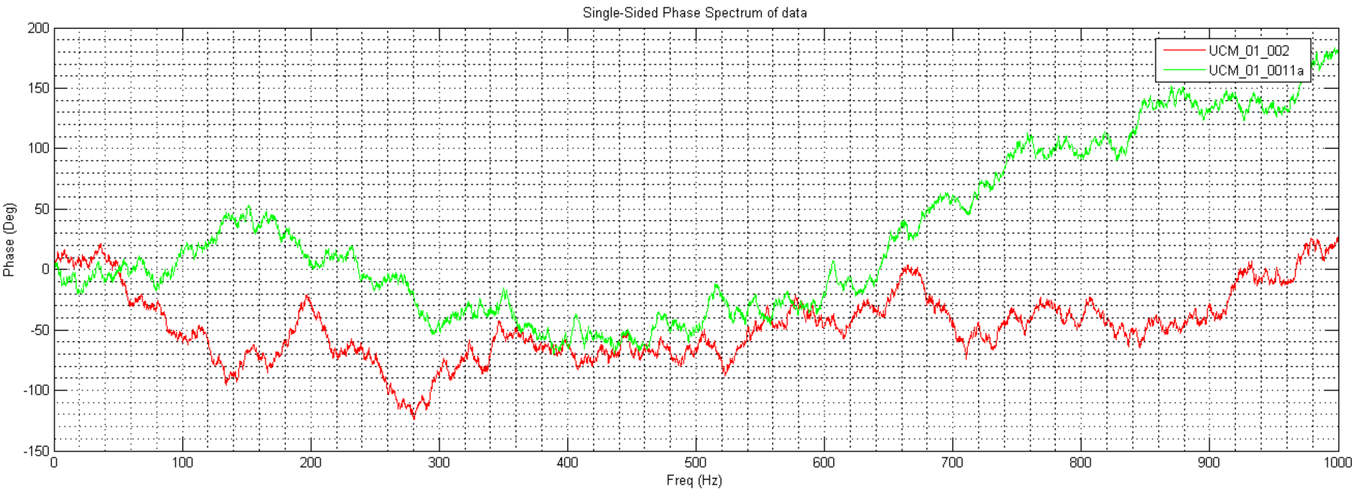


Figure 8.2 UCM+ versus UCM, FFT with amplitude and phase information

8.1.4 Test conclusion

The UCM+ has an improved performance when doing the same measurements with an offline down-sampled sample frequency. The new noise is only about 80% of the original noise. The origin of this improvement can be seen in the FFT plot of Figure 8.2, where the ratio between signal and noise has increased in the UCM+.

8.2 Test 2: UCM+ with MS3110 input shaping

The same test set up is used as the previous tests, only different firmware is now loaded onto the UCM+, which attempts to shape the input sensitivity of the MS3110 according to changes in the input capacity. This increases the sensitivity, but lowers the input range.

8.2.1 Test set up

The test set up is the same as in the previous test.

8.2.2 Measurement procedure

The same measurement procedure is used as in the previous test, only 3 different ranges are compared to each other. The first range, or the full range, is a measurement range of 10pF, the second measurement range is a 1pF measurement range situated around the measured capacity and the third measurement range is a 0.1pF measurement range situated around the measured capacity. The next test contains similar graphs with these ranges, only this test shows the results over a wider frequency range (up to a sample frequency of 7.5kHz).

8.2.3 Test results

Figure 8.3 shows three times the 3σ deviation expressed in attofarads versus the used sample frequency in three ranges. The noise is almost 3 times decreased when moving from full input range to the 1pF range. Further reduction of the input range to 0.1pF decreases the noise a little more than 2 times.
Figure 8.4 shows the result of a simple algorithm which switches between different ranges on the fly. The graph shows the time plot of the UCM+'s output when manually connecting different capacitors to the input. The two biggest problems that occur are & visible in this figure:

1. The first sample after a change to the MS3110 registers has been made is incorrect. This can be solved by simply giving out the same value twice after a register has been changed.
2. An absolute jump is made when switch to another range. The absolute value decreases when the range is decreased. Offsets, preferably calculated in a calibrating procedure, will have to be included in calculations when a new range becomes active.

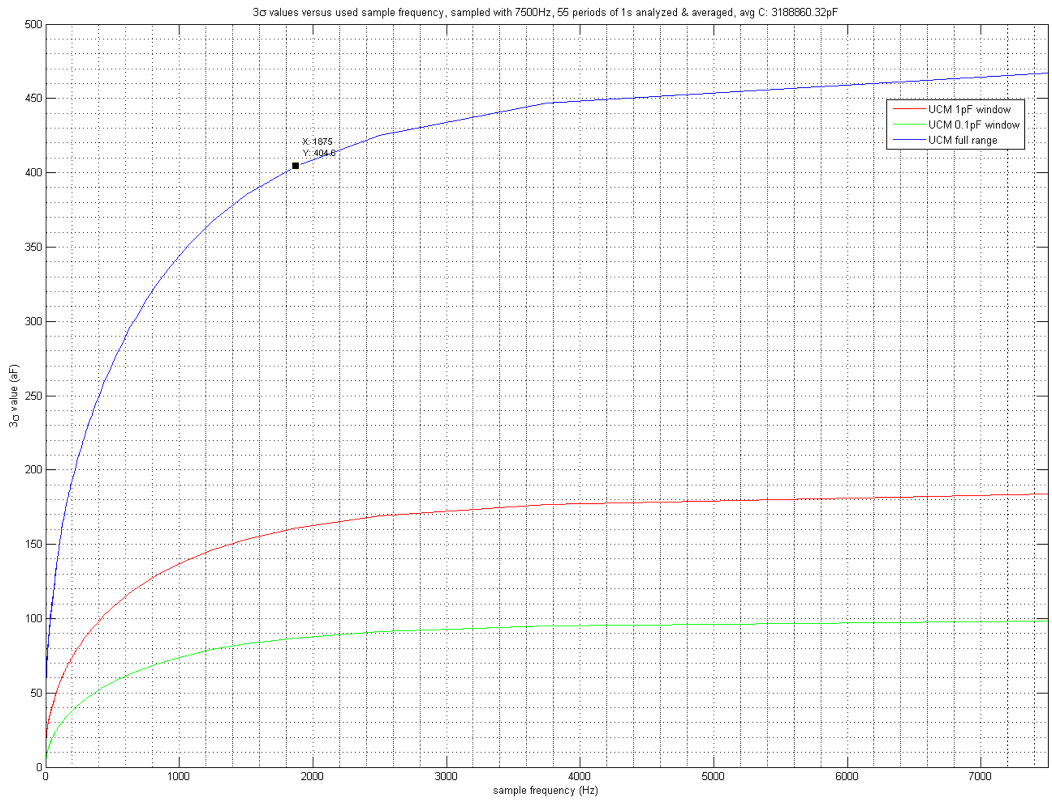


Figure 8.3 3σ values versus the used sample frequency in three ranges

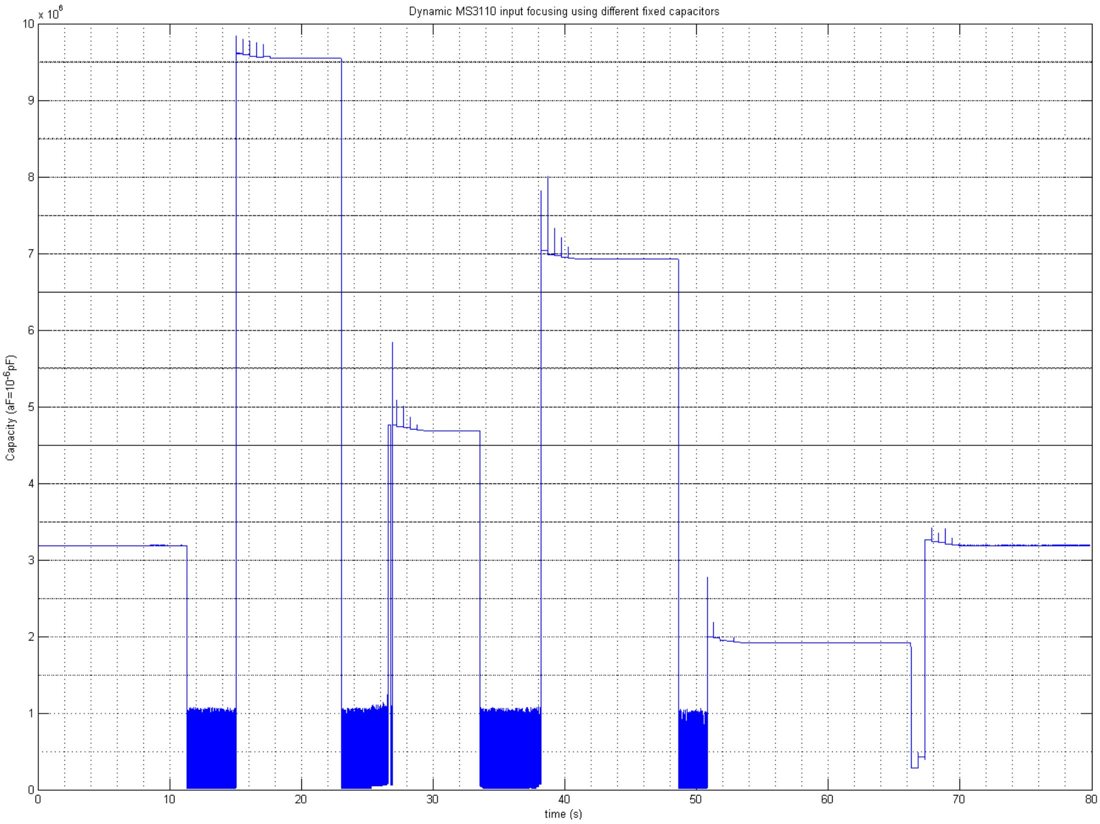


Figure 8.4 Dynamic input shaping by switching between various fixed capacitors

8.2.4 Test conclusion

Input shaping provides a way to increase the UCM+'s resolution more. Different implementations can be used to allow the UCM+ to use this technique. The most perfect solution would be a system that could change the input range on the fly without any user interaction or noticeable jump in output results. Another use would be a selectable range or a command which alters the range so the user has full control when and how the UCM+ switches to another input

No matter what implementation is used, the problem that has to be solved anyway is the absolute difference when switching to different ranges. The gain and offset registers are both specified with a 20% margin. The only way to keep this spread out of the UCM+ is by calibrating it and store additional offsets in a look-up table. It would only be necessary to create a table with correction factors for the selectable gain and offset values. Prior to use, the system would have to be calibrated by using a fixed capacitor and varying the gain and offset registers alternately. An equation will have to be found to calculate the new offsets by analyzing the jumps in the UCM+ output when switching to other MS3110 settings.

8.3 Test 3: UCM+ versus PI signal conditioner

The same test set up is used as the previous tests, only similar settings are chosen to match with a previous test done with a PI sensor and signal conditioner. The goal is to try to create an even test between both electronics to show a meaningful comparison. Physik Instrumente is market leader in developing capacitive sensors and electronics which are able to achieve sub-nanometer accuracy. A test has been done at JPE with a single electrode PI sensor with signal conditioner. Tests in this paragraph are a comparison of the UCM+ to the PI sensor with electronics. Since the PI sensor is no longer available at JPE, the UCM+ is used to measure a fixed capacitor which should have a capacitance about equal to the capacitance of the PI sensor in its test setup [10].

8.3.1 Test set up

The same set up is used as in the previous tests. To compare the data with the PI sensor, the old log file is that was used to create the graphs in [10]. [10] Also contains a complete description of the test set up and how the results were obtained. To make the comparison easier, the most relevant data is reprinted below:

PI set up:

- Sensor used: PI D-510.020 [12]
  - Sensor area: 11.2mm^2
  - Measurement range: 20µm
  - Minimum gap: 10µm
- Sensor electronics: PI D-852.10 signal conditioner [13]
  - Output: -10V - 10V
  - Sensitivity: 1nm/mV
  - Sample frequency used: 3kHz
- Power supply: PI D-852.PS Power Supply
- Voltage meter: Keithley 2000 Digital Multimeter
  - Sample frequency used: 1kHz
- Log file used (1s): RMetz_Logs_PID510.020_Keithly_11-9-08_ACLF_1000_Hz_V.DAT
  - Converted to: RMetz_Logs_PID510.020_Keithly_11-9-08_ACLF_1000_Hz_nm.DAT.txt

The old log file is converted to create a similar log file as with the UCM+; a column with time and a column with measurements in nm. The PI signal conditioner transforms the measured value directly into a signal corresponding with a gap displacement between sensor and bloc surface. Since no data regarding the measured capacity is available, the capacity has to be calculated back by converting the initial gap width back to a capacity using Equation 5.2. The PI sensor was placed fixed in a position half of the measurement range, giving out a voltage around 0V. If default setting was used, this should correspond with a capacity of 4.961pF.

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

$$\mathrm{d(m)} = \text{Gap distance between sensor plates expressed in } \mu\mathrm{m}$$

$$\varepsilon_0\,\mathrm{(F/m)} = \text{permittivity of free space, equals } 8.854187 \times 10^{-12}\ F/m$$

$$\varepsilon_r\,\mathrm{(F/m)} = \text{relative static permittivity of the material between the plates, } 1.00054 \text{ for air}$$

$$\mathrm{A(m^2)} = \text{overlapped sensor area}$$

Equation 8.2 Conversion between capacity and gap between sensor plates

Since the PI sensor is no longer available at JPE, a capacity around 4.9pF inside the aluminum box will be used to 'simulate' static position of the sensor. Three different ranges or sensitivities will be tested with this 4.9pF capacitor. In the first range, the full output voltage swing (0.5V - 4V) of the MS3110 corresponds with 0pF-10pF, in the second range a swing of 4.4pF-5.4pF corresponds with the full output voltage swing and in the third range it corresponds with 4.85pF-4.95pF.

UCM+ set up:

- Sensor used: 4.9pF fixed silver MICA capacitor
- Sensor electronics: UCM_01_002
  - Output: 0.5V – 4V
  - Sensitivity:
    - Range 1: 2.86 pF/V (11.52nm/mV)
    - Range 2: 286 fF/V (1.15nm/mV)
    - Range 3: 28.6 fF/V (0.115nm/mV)
  - Mechanical range:
    - Range 1: 188µm
    - Range 2: 4.2µm
    - Range 3: 0.42µm
  - Sample frequency used: 1kHz (MS3110 output bandwidth limited to 500Hz)
- Log files used:
  - Range 1: UCM2_RAW__11-6-2009__12-18.TXT_No0_SF_1000Hz_RAW.txt
  - Range 2: UCM2_RAW__11-6-2009__12-08.TXT_No0_SF_1000Hz_RAW.txt
  - Range 3: UCM2_RAW__11-6-2009__12-11.TXT_No0_SF_1000Hz_RAW.txt

The third script used to analyze the data also analyzes log files obtained when measuring the highest and lowest estimated sensor capacitance (best and worst case), to provide some reference data over the full range of PI D-510.020 sensor. Data from this PI sensor however only exists for the 4.9pF range. The UCM+ test setup is identical to Figure 5.9, only now the redesigned UCM+ is used.

8.3.2 Measurement procedure

The same measurement procedure is used as the previous tests with the UCM+. The PI log file and 3 UCM+ logs are then processed by various MATLAB scripts to analyze them and light out the differences. Three different scripts are used which all use different ways to analyze and represent the data. Since the PI log contains only nanometers, all UCM+ values from the logs will also be converted to nanometers using the conversion from Equation 8.2. All the UCM+ scripts can be found in: *G:\JPE\Control\UniversalCapacityMeasurementIntegration\WERKdir_E\06_MATLABdocs.*
The first script performs a power density spectrum analysis on the data. This analysis is comparable to a Fourier transformation, only now the power of the signal is analyzed (signal^2). A cumulative sum is done on all the PSD coefficients which are used to create a power density graph, showing for increasing bandwidth the total frequency power content of the signal. Script name: *Use_Calc_PSD.m.*
The second script is the same as used in the previous tests, only now it calculates the 3σ values expressed in nanometers. It also calculates the FFT coefficients. Script name: *Process_raw_data.m.*
The third script is the same MATLAB script used to analyze the PI data. It used a variable fourth order low pass Butterworth filter to cut off the signal at frequencies up to 50Hz. The filter is moved by 1Hz in every run from 5Hz up to 50Hz. The peak-peak noise in nanometers is calculated over the filtered data. Script name: *UCM_vs_PI_BWT.m.* Original script used for PI data: *G:\ASML\BWT (Bolted Wafer Table)\WERKdir_SDEV\Data Analyse\MatlabScripts\lowPassFilter_sampleData_Capsens.m.*

8.3.3 Test results

The figure below shows the graphical representation of the 4 logs. All 3 UCM+ logs are about 10 seconds long; the PI log used in [10] was only 1 second long.

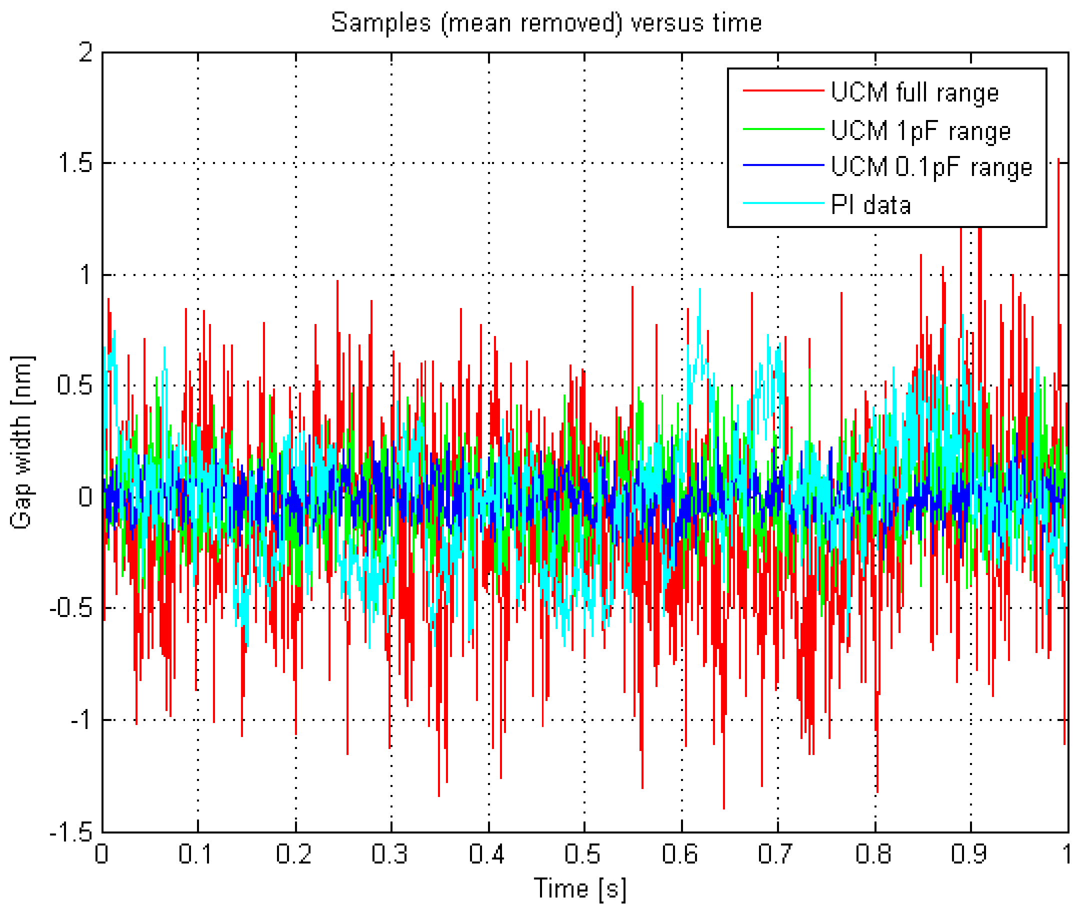


Figure 8.5 Time plot 4 used log files, only 1s displayed of each log

8.3.3.1 Output first script: cumulative PSD

Figure 8.6 shows the result of a power spectrum density analysis. The calculated values, expressed in nm^2/Hz, are cumulative summed up to create the figure. The figure here displays the power of the input data in nm^2 versus the signal bandwidth in Hz. For example, with a 200Hz bandwidth, the PI data has power density of $0.1nm^2$. Since the measured signal has a frequency of 0 Hz, increasing values in the other frequencies indicate more noise.
When the UCM+ is set to measure at a full range, the PI is a winner. This was to be expected due to the significant difference in sensitivity between PI and UCM+ here (11.5x). However the second range of the UCM+, which has a comparable sensitivity, shows a significant improvement in unwanted noise addition over the whole detectable frequency range. The frequency content in the 0.1pF range of the UCM+ is even lower.
It is also possible to convert the PSD to a graph showing the density expressed in nm for the continuous bandwidths, Figure 8.7. It is converted to show the double sided spectrum at the positive side (spectrum values at –f + f). The value in nm signifies an amplitude value for all the noise sine's added together in the horizontal frequency band. At 0Hz, no AC components are present to the sum starts at 0 here. Higher values signify more noise.
Figure 8.8 is the same graph as Figure 8.6, only now is the PI line divided by the three UCM+ range lines. A value above one indicates an UCM+ win over the PI data. The UCM+ has the most performance win in the lower frequency ranges.

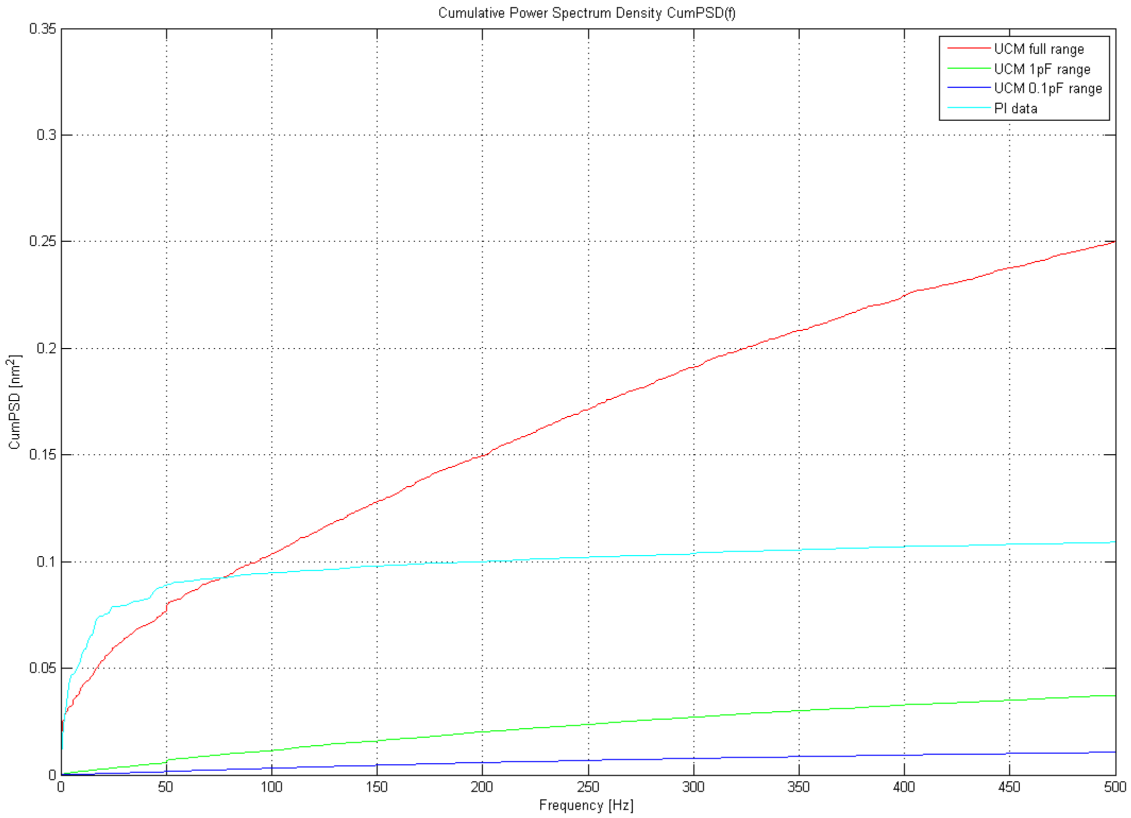


Figure 8.6 Cumulative single sided PSD plot 4 used log files, bandwidth versus power density in nm^2

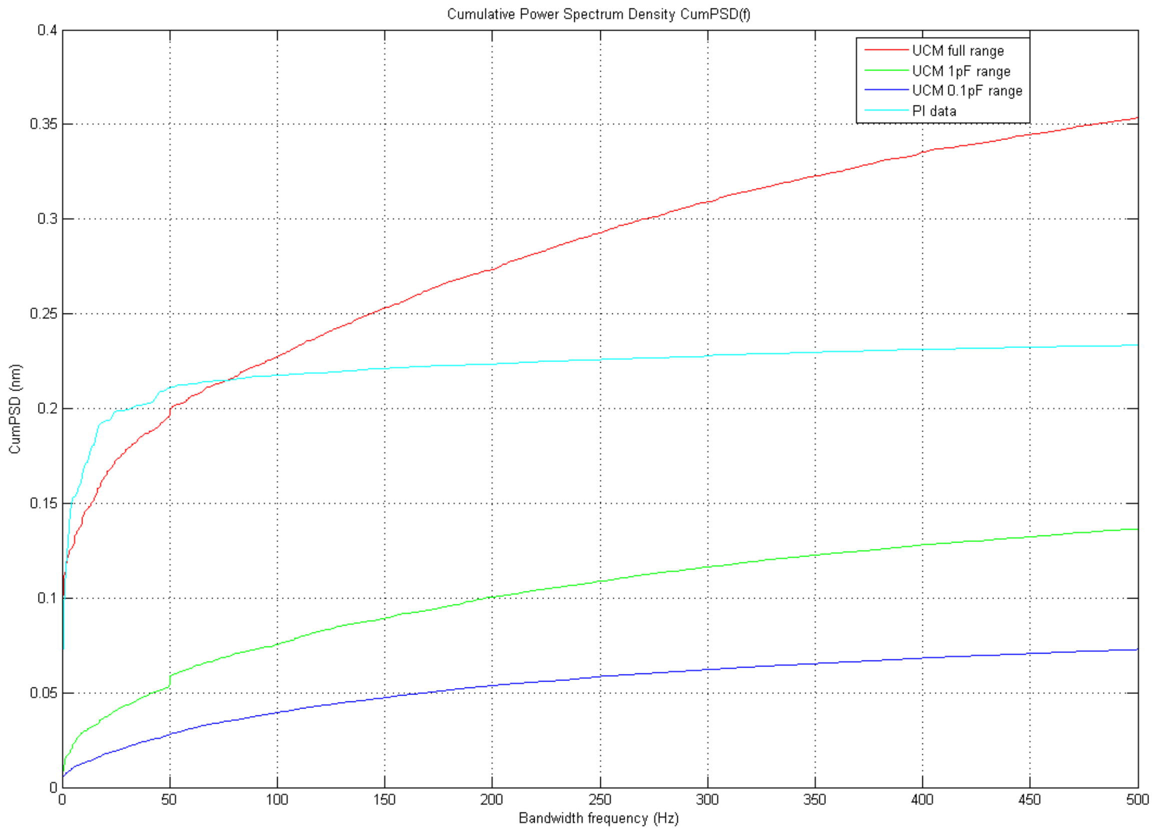


Figure 8.7 Cumulative spectrum double sided density plot 4 used log files, bandwidth versus spectral density in nm

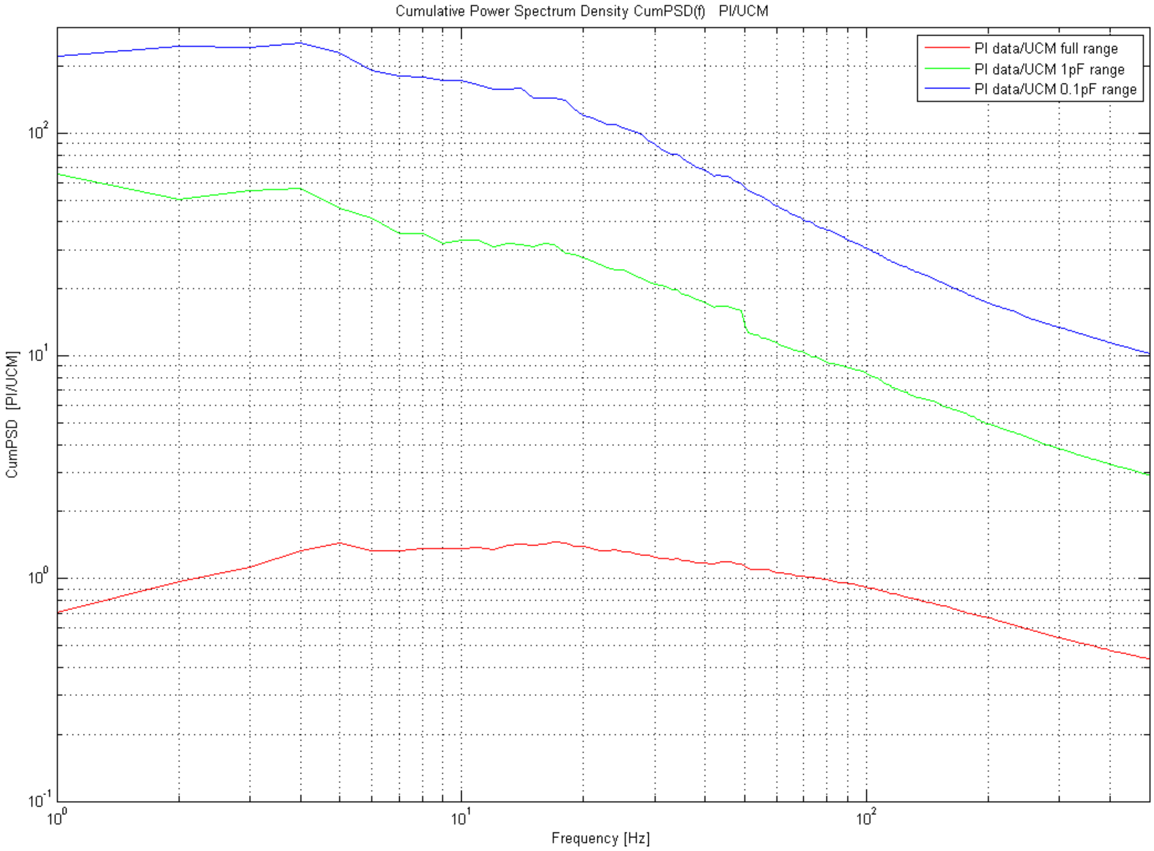


Figure 8.8 Cumulative PSD plot PI data divided by three UCM+ ranges

8.3.3.2 Output second script: noise versus used sample frequency & FFT

Figure 8.9 shows an output graph of the noise analysis expressed in 3σ values in nanometers. The same relation in the different graphs is seen as shown by the previous script, only with different ratios. The PI log shows a noise value of 0.93nm at 1kHz, the three UCM+ logs show corresponding from full to 0.1pF range: 1.44nm, 0.58nm, 0.31nm. The PI sensor datasheet specifies a static resolution of <0.2nm (<0.001% of 20µm) with a bandwidth of 10Hz. Figure 8.9 shows that the UCM+ can meet this resolution in the 0.1pF range with a bandwidth around 150Hz. In the 1pF range, this resolution is met with a bandwidth of 40Hz. However, please note that the worst case performance occurs when the capacity is low. This would imply a gap width of 30µm for the used PI sensor which corresponds with a capacity of 3.3pF. The best case scenario would be with a very small gap width, in this case the smallest gap, 10µm, corresponding with a gap capacitance of 9.9pF. Measurements with these values included have been analyzed with the next script.

The FFT plot shows a surprisingly big difference between the amplitude of the PI plot and the UCM+ plots. The amplitudes in dB have been shifted along the y-axis so that 0dB equals 0Hz, in this case the most present frequency. It could be that a lack of data from the PI measurement makes the FFT inaccurate, since the FFT results do not match with the other script results. The SNR shows a ratio of at least 50dB (100,000x) between PI data and UCM+ data, although the PI data does not have the highest amplitude at 0Hz, but around 1Hz. Unfortunately, all logged PI results contain only 1000 samples. A more extensive FFT analysis should be performed to display the phase characteristic more accurately for which more PI data is also needed.

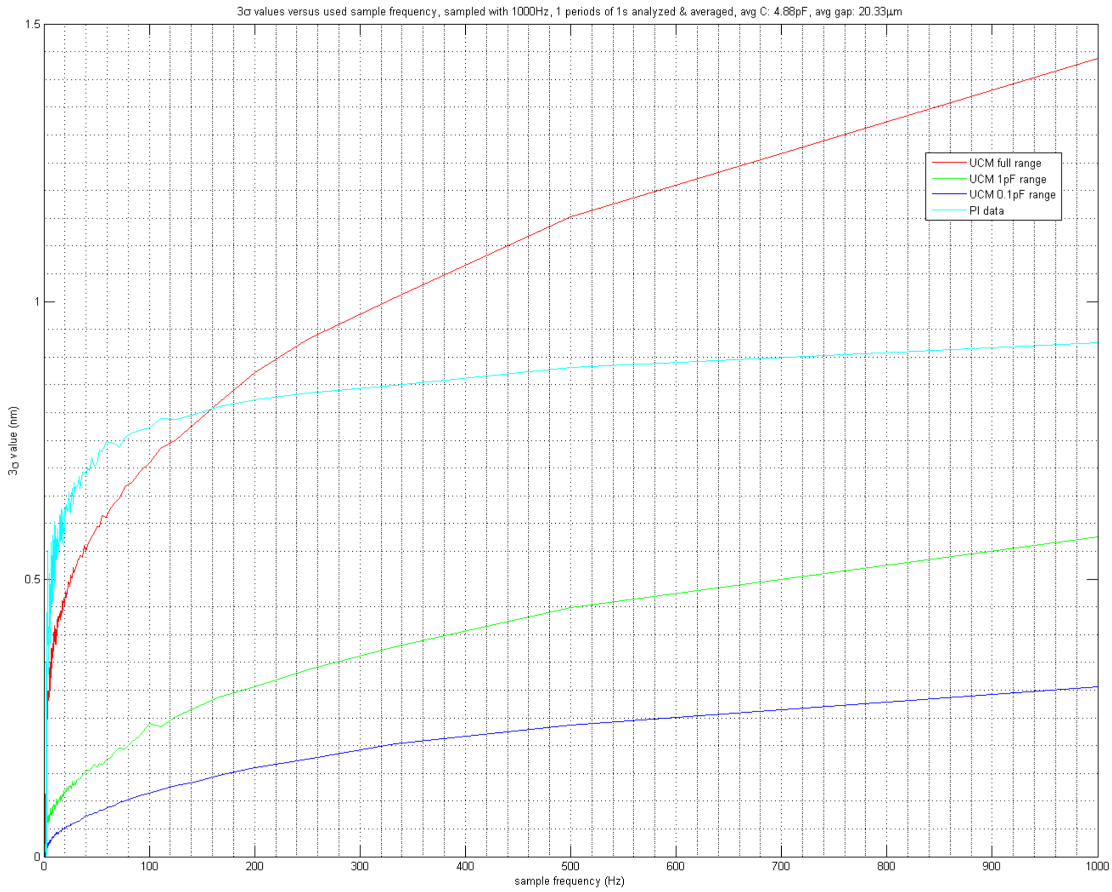


Figure 8.9 3σ values in nm 4 log files versus used sample frequency

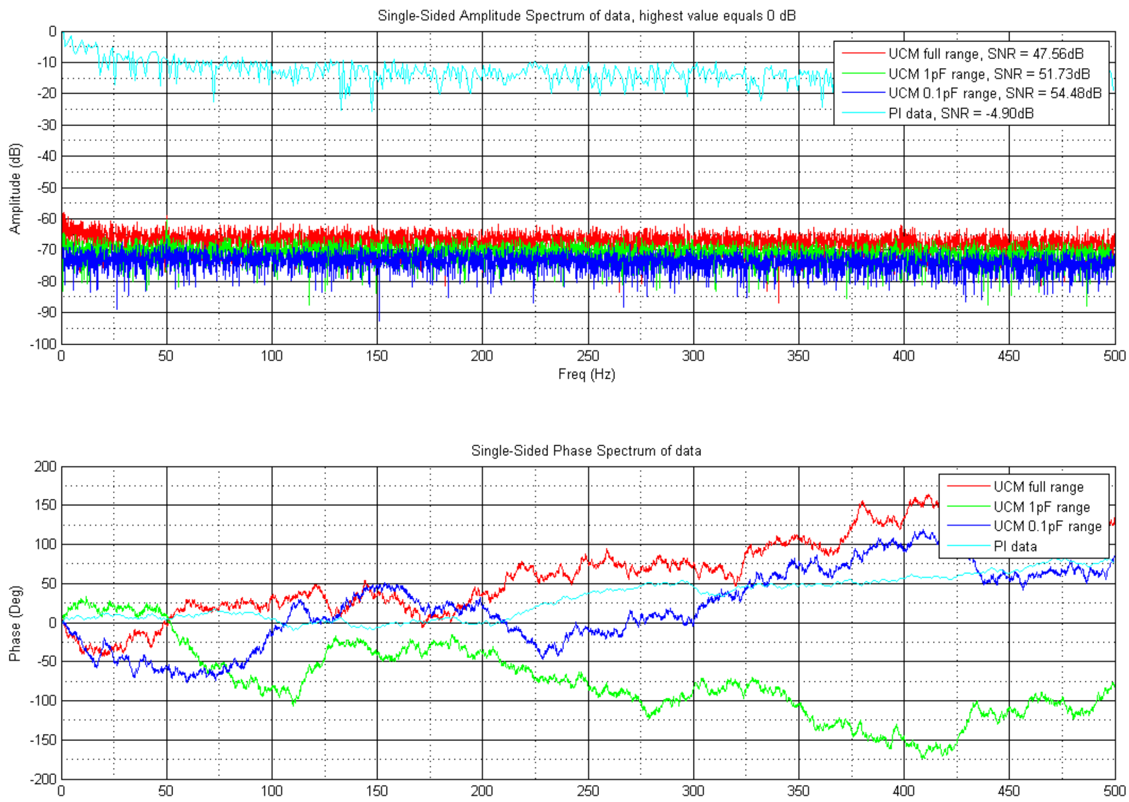


Figure 8.10 FFT analysis 4 log files, amplitude in dB and phase in degrees

8.3.3.3 Output third script: noise versus moving low pass filter per 1Hz

The PI sensor test set up described in [10], was analyzed with a script looking for the peak-peak noise in a dataset after filtering it with a fourth order low pass filter. The filter is moved in 1Hz steps from 5Hz up to 50Hz. Please note that these graphs show the bandwidth horizontally and not the sample frequency. Figure 8.11, Figure 8.12 and Figure 8.13 show respectively the peak-peak noise when PI sensor is placed in the middle position (gap = 20µm), widest position (gap = 30µm) and smallest position (gap = 10µm). The UCM+ electronics show the worst signal to noise ratio when measuring lower capacitance, so the worst peak-peak values are obtained by measuring lower capacities. The sensor electronics will be limited by their performance in this area.
Please note that only data from the PI sensor in the middle position is available. The PI data curve in the other 2 figures is identical to the first one; it is only displayed as a reference, but it is not clear how the PI signal conditioner is affected by measuring higher or lower capacities.
Figure 8.11 however shows that with this analysis the data from the UCM+ set to full range comes already very close to the PI data.

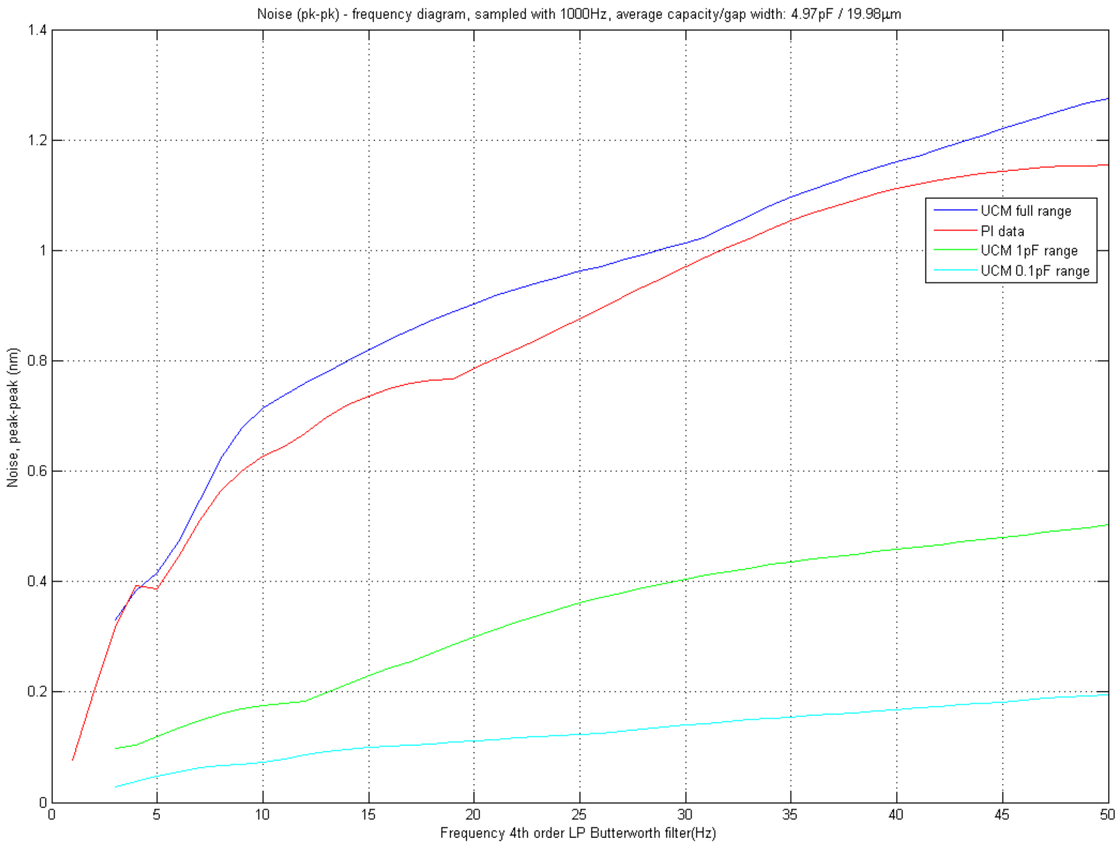


Figure 8.11 Peak-peak noise UCM+ versus PI using roughly same capacity on both inputs

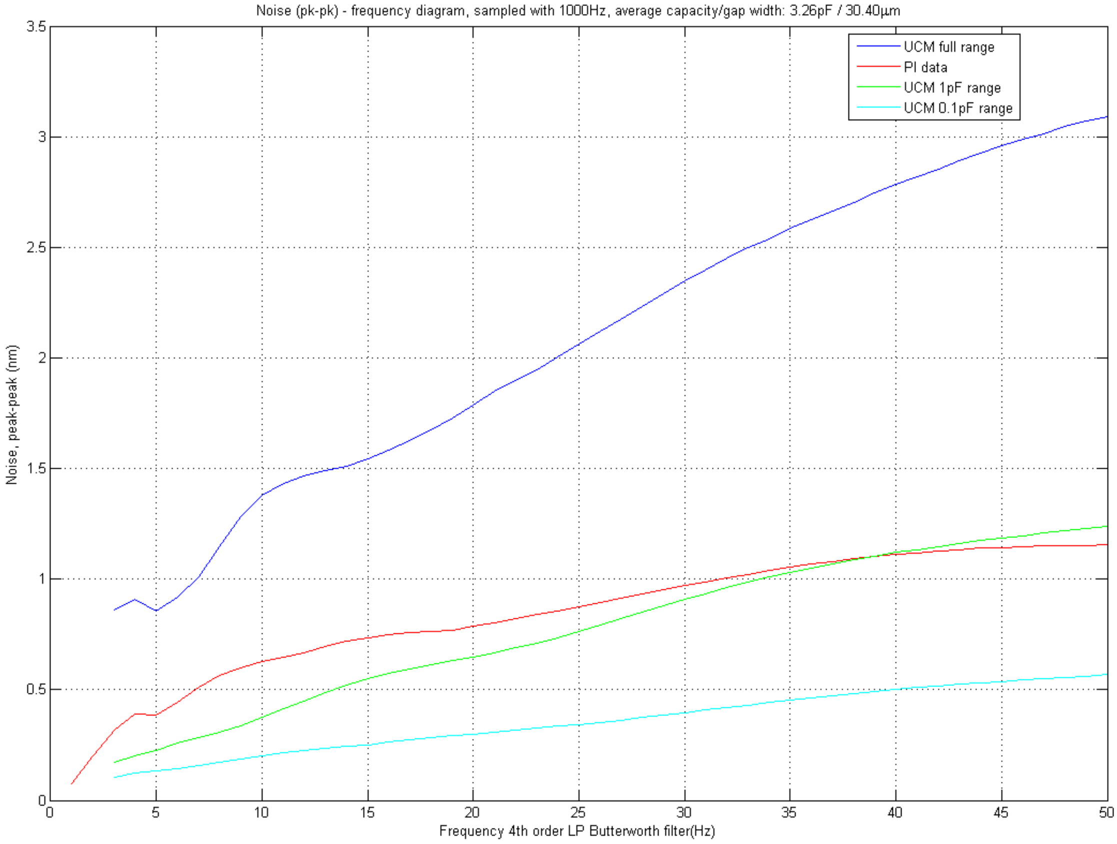


Figure 8.12 Worst case peak-peak noise UCM+ when referred PI sensor used (PI data ≈ 5pF, only for reference)

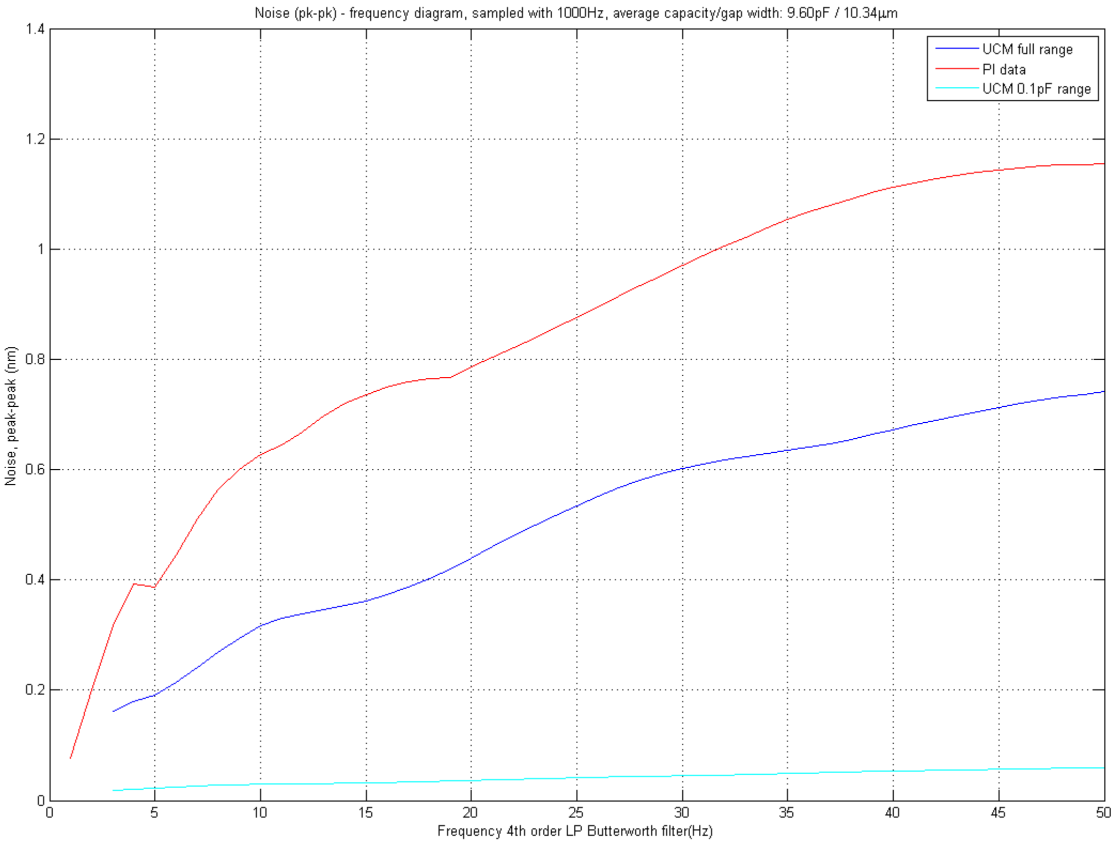


Figure 8.13 Best case peak-peak noise UCM+ when referred PI sensor used (PI data ≈ 5pF, only for reference)

8.3.4 Test conclusion

Test results show that the UCM+ can already compete with the PI E-852 electronics when the full input range is used, especially when used in lower frequency areas. The second script shows that increasing the sensitivity of the UCM+ to a value comparable to the PI electronics, the PI noise can be cut in half (1pF range) or even one third if the sensitivity is further increased (0.1pF range).
Figure 8.9 and Figure 8.11 show that the UCM+ electronics are capable of obtaining the mentioned static resolution in the datasheet of the PI D-510.020 sensor. The PI sensor should be able to obtain a 0.2nm resolution when bandwidth is limited to 10Hz. The dynamic resolution of the PI sensor was not tested, but since this value is specified for a bandwidth of 10kHz, it cannot be simulated with the UCM+. The UCM+'s maximum sample frequency is 7500Hz when one UCM+ is used, limited by the used CAN bus. The next available sample frequency that can be set in the used ADC is 15kHz, which cannot be transported real time, due to the limit of CAN bus speed.
It should be noted that the used PI reference sensor is single probe sensor, which measures the capacitance in a different way. PI also has two electrode sensors, sensors with two plates. These sensors are claimed to have a 0.075nm resolution for the smallest sensor (0.0005% of 15µm, PI D-015.00 sensor).

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The original goal was to qualify the UCM prototype using the piezo controlled stage. Tests done with the stage and reference capacitors lead to several conclusions on how the total piezo stage performance could be improved. Since the time was limited, the conclusion which could prove to have the best results was carried out, the redesign of the UCM prototype the UCM+.

The first part of the internship involved comparing the old capacitive measurement system UTI with the new system UCM (prototype) implemented in the piezo controlled stage. On a short term basis, the first UCM had a dynamic range about 3.7 times the dynamic range of the UTI. On a long term basis, this ratio is increased to 5.6x. This shows that the performance of the UCM is also steady over time. These ratios apply to the increase in capacitive measurement capabilities. The UCM also had a sample frequency about 25x that of the UTI. This is enough prove that the UCM outperforms the UTI. The only question now is, whether the piezo stage is now limited in resolution by the UCM, or other components of the system.

More tests showed that the UCM achieved comparable results with fixed capacitors, leading to the conclusion that the limiting factor of the PCS still is the capacitive measurement system. This conclusion was strengthened by differences seen between various UCM's, the same differences occurring with the stage or fixed capacitors connected.

The differences in the UCM's performances were caused by untrimmed MS3110's and the used single sub-d connector, which introduced crosstalk between different sensor channels. The best way to even out the performance of different UCM's is by trimming the MS3110 prior to assembly and the usage of separate BNC connectors for each different UCM. Signal lines will be shielded and placed far apart from each other this way.

This conclusion led to the development of a redesigned, more compact UCM+. The UCM+ has a noise level about 80% of the original prototype and is a lot cheaper. The redesigned UCM has more functionality and the firmware is more versatile.

One very important conclusion is that the developed capacitive measurement system cannot characterize its performance in one number. Performance is not only dependable on the used sample frequency, but also dependent on the input capacitance and settings of the MS3110. The MS3110 has the potential to achieve a very high resolution, but the dynamic range of 10^5 can never be met with the developed UCM+ with high sample rates. Only a sample frequency of 10Hz the UCM+ would come close to this spec. Filtering could improve results, but this also limits the usable input frequencies, since frequencies with too much phase shift cannot safely be used in a closed loop system.
The resolution can also be increased by adjusting the gain factor inside the UCM+. This leaves the phase characteristic unchanged, only this way the input range is much smaller, so the dynamic range also decreases. When lowering the input range 10 times, the noise is only lowered 2 to 3 times. This leaves the dynamic range also 3 to 5 times smaller, but there are opportunities here to achieve a high resolution without effectively altering the input range of the UCM+. The UCM+ simply has to extend or move the input range when the input tends to increase or decrease a lot. The end user will be able to use the UCM+ with a very high 'simulated' dynamic range, but in fact only the sensitivity increases and the dynamic range decreases, invisible for the end user.

The performance of the UCM+ is worst when measuring small capacitance. So the UCM+ could be characterized by its noise value at that capacity. Only each sensor will use a different capacitive range, or the gap width is adjustable so the lowest value is not fixed. In order to answer the question, How good will the UCM+ perform using my sensor?, the following constraints have to be clear: the total measurement range and the surface of the sensor. With this information, an estimate can be made of the lowest occurring capacity. This capacity can be looked up in one of the graphs showing the noise versus sample frequency from a similar capacitance (Figure 8.3 if C_{MIN} = 5pF). Depending on the used sample frequency, a good estimate can be made then of the expected noise. This noise will limit the sensor performance over the full range, if the full range is used of course. If the capacitive noise is expressed in gap width it is also the limiting factor of the mechanical resolution of the sensor.
The recommendation part contains a section with a method for designing a capacitive sensor in order to get the most performance out of the UCM+.

The UCM+ was also compared to electronics from PI, a market leader in the development of capacitive measurement system. The UCM+ came close to the PI data when used in full range, but when the sensitivity was increased of the UCM+, it outperformed the PI data. The UCM+ can definitely be a competitive player with top leading developers in the world of high resolution capacitive measurement electronics, also the output of the UCM+ is already digital, PI's output is still analog.

9.2 Recommendations

9.2.1 PCS upgrade recommendations

The total performance of the piezo controlled stage can be further enhanced with the following points:

- Calibrate each sensor with its optimal initial sensor gap. It is estimated in '5.5.4' that careful calibration can increase the resolution almost by a factor 2.
- Redesign the controller to be more dynamic. The UCM can provide data at a much higher rate. The current controller is not optimized for this and does also not use the UCM's information accurately enough. Especially the rotating axes show less improvement compared to the straight axes. The current controller is limited in its software not to change the piezos anymore if the position is within a certain range of the set point.
  It has to be investigated first what frequencies can be allowed in the stage, but older tests show that the stage has its first eigenfrequency around 250Hz. The UCM could for example sample with 500Hz while the piezo's are driven with 100Hz.
- Perform the UCM resolution increase recommendations.

9.2.2 UCM+ recommendations

- Optimize the input/output shaping routine of the MS3110 so that either automatically, or by commands the resolution can be increased. The biggest problems are the jumps in absolute capacitance. The creation of a lookup table with a calibration routine could erase the jumps. The lookup table would only need to have a correction factor for each register setting. Only 2 registers are changed in the input/output shaping routine, so this leaves the table small.
- Build a new case with 6 redesigned UCM's inside. Six new UCM's can be built up and put in one case. Each UCM can slide its BNC connectors directly through drilled holes in the case. A power supply should be placed outside the case which converts 230VAC to 7.5-10VDC. The case should have one power connector for the 7.5-10VDC input, one sub-d connector for the CAN bus and 12 BNC connectors in the front where 6 two electrode capacitive sensors can be connected.
  Each UCM should have a proper jumper configuration. Only the CAN busses all have to be connected by one bus. The power supply also has to be connected. Leave JTAG and RS232 headers unconnected.

9.2.3 Capacitive sensor design recommendations

During the analysis off all the test results, certain optimal conditions for obtaining the best sensor results became clear. In a mechanical design, certain mechanical constraints can be used to create an optimal sensor with optimal placement to obtain the highest mechanical (& electrical) resolution.

Specifications at design stage are a stroke between which two surfaces vary (max gap – min gap). The optimal sensor can best be made, with a known stroke. A choice can then be made in the min and max capacity the sensor should output, making it easier to create a sensor with a higher resolution. In this case, the designer only has to specify a min and max capacity and the stroke to measure. The UCM+ performs optimal in a 5-10pF range, so these values will be C_{MIN} and C_{MAX}. The only thing left to calculate then is the min and max gap of the sensor and the sensor surface. Gap_{MIN} is always equal to the stroke when the optimal sensor design is used. Equation 9.1 shows the solution to finding these values.

$$C_{MIN} = \frac{\varepsilon A}{GAP_{MIN} + stroke} \quad C_{MAX} = \frac{\varepsilon A}{GAP_{MIN}}, \text{ solving both equations for } GAP_{MIN} \text{ and } A \text{ gives:}$$

$$A = \frac{C_{MIN} \cdot C_{MAX} \cdot stroke}{\varepsilon\left(C_{MAX} - C_{MIN}\right)} \quad GAP_{MIN} = \frac{C_{MIN} \cdot stroke}{C_{MAX} - C_{MIN}} \quad GAP_{MAX} = GAP_{MIN} + stroke$$

Equation 9.1 Calculation A & $GAP_{MIN/MAX}$ for known stroke and capacitance limits (stroke (µm))

If the desired mechanical resolution is also specified, it is possible to calculate the needed capacitive resolution at C_{MIN}. Comparing this resolution to resolutions measured with the UCM+ at 5pF give a good estimate of the achievable mechanical resolution using the UCM+ and a given stroke. An excel worksheet is made which automatically calculates the optimal sensor values with the known specifications. The worksheet can be found in *G:\JPE\Control\UniversalCapacityMeasurementIntegration\WERKdir_E\01_Documents\Opt_Sensor_Calc.xls*. It also has the possibility to estimate the optimal stroke for a given sensor or other optimal conditions with different input specifications.

APPENDIX A: XPC INSTRUCTIONS MATLAB 7.0

A.1 Useful commands on xPC host

The following is a short list of commands which can be given in the MATLAB command window to quicken tests. A more extended list can be found in [8]. The commands in this document and listed below are tested and work in MATLAB release 14, xPC Version 2.5.

xpcsetup Opens window with XPC settings regarding communication with target, compiler selection and xPC Target Embedded Option. This option sets the way to load data on xPC target. Select stand-alone to create files which can be copied to the target by a floppy disk, or use DOSLoader to transmit the model over the selected communication link. A loader has to be running on the target with the same settings as visible on the xPC Target Setup screen. The loader can be created by pressing BootDisk. The boat loader is copied on a formatted floppy which can be run on the Target in a DOS environment. The screen below shows the settings for an Ethernet communication over the JPE network to communicate with the PC/104 used to control the PCS. The CANLibrary only has to be added when a CAN extension board is used.

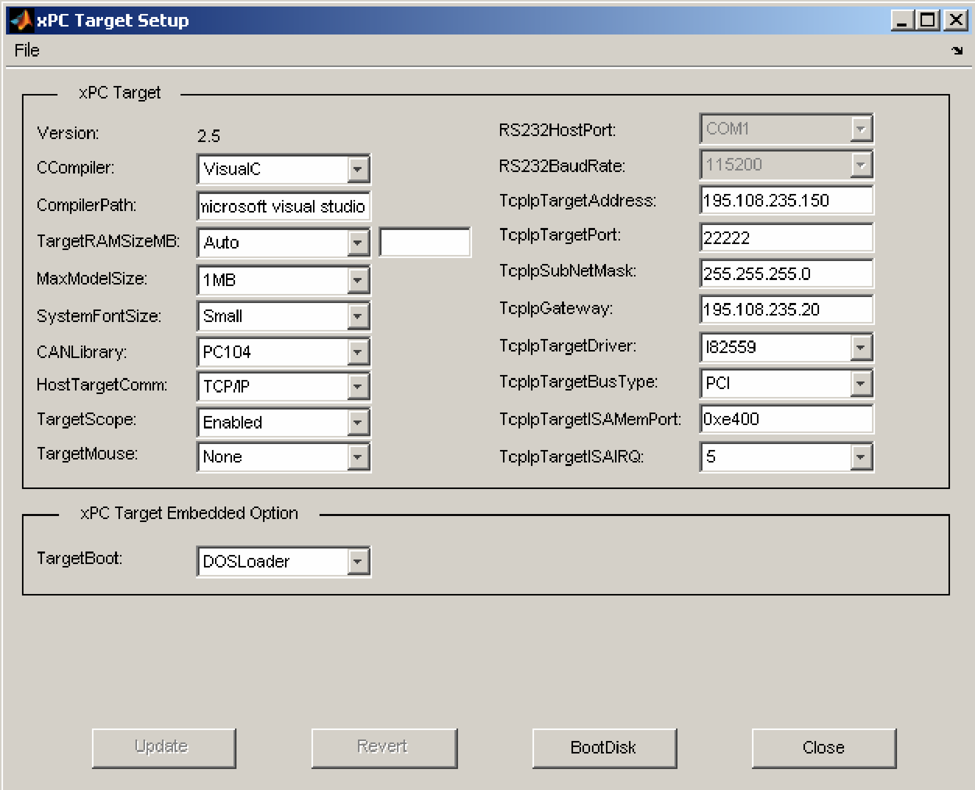


Figure A.1 xPC Target Setup screen with settings for PC/104 used to control PCS @ JPE

rtwbuild('model_name') Builds and runs model on target PC. Model has to be opened first with *opensystem('model_name)*.

tg = xpc This command will create an xPC object with the name 'tg'. Simply typing 'tg' will give the current status of the xPC model. The parameters visible can be modified or stored. The following commands show a few examples.

tg.StopTime = 60 Set stop time of model run to 60 seconds.

opTime = tg.TimeLog Store time log (if present on target PC) in opTime variable. All available time data will be downloaded to host PC and then stored.

setparam(tg, 2, 40) This will set tunable parameter 2 of tg xPC object to 40. If this parameter does not exist an error message will be displayed, else the old and new value are shown.

getparam(tg,2) Retrieve the value of tunable parameter 2 of tg object.

xpcrctool xPC remote connect tool. Displays live information of current loaded model. Allows the user to start/stop the application modify parameters, log data, take screen shots of xPC target, load different models onto host and much more.

A.2 Short instructions running & debugging PCS xPC application

Two options are available to load the data onto the xPC PC/104 target. The application can be compiled in Stand Alone mode, which allows the user to copy the application on the Compact Flash card installed in the PC/104 system, or the application can be downloaded by an xPC DOSLoader running on the xPC target. The previous subparagraph provides information how to configure the host and target with the command *xpcsetup*.
After *xpcsetup* has been completed, the user can load the model, usually named *assemxxa.mdl*, where *xx* stands for the version number. Before building the application, an M-file called *PCS_model.m* has to be executed first to initialize and set all variables used in the model. With the model open, press CTRL+B in the model window to build the model, or select *Tools→Real-Time Workshop→Build* in the model window. This builds the window and if no errors appear the model is loaded onto the target, or the standalone files are created in a directory called *assemxxa_xpc_emb* in the model directory. Please note that a C(++) compiler has to be installed in order to compile the model (WatCom or VisualC compiler can be used).
Run and control the model using the command described in the previous paragraph or use the command window in the xPC target PC. Simply press ‘c’ here and a command prompt is showed. Simple commands, like *Start*, *Stop* or *Reboot* can be used. Other parameters can modified by typing ‘px = value’, where x is the parameter number. A list of all the parameters available can be seen in the file *assemxxa_pt.c* in the build directory *assemxxa_xpc_rtw*.
If the application is downloaded from the host PC and an xPC object called ‘tg’ is created, the list of tunable parameters can be downloaded using *tg.ShowParameters = ‘on’*. Modifying the parameters can then be done with the *setparam()* command.
An instruction manual regarding the operation of the stage with the firmware is also available [9].

APPENDIX B: MS3110 TRIMMING PROCEDURE

This appendix contains a step by step procedure to trim the MS3110 in its optimal performance settings.

The following equipment has to be set up prior to the trimming:
- Dual lab power supply, one output set to 16V, one output set to 5V, with power cables
- MS3110BDPC evaluation board with MS3110 placed in ZIF socket (pin 1 placed right under)
- Parallel port cable (centronics cable)
- Cables with antenna grapplers to measure test points on MS3110BDPC evaluation board
- Keithly 2000 multimeter to measure voltages and currents
- Oscilloscope to measure excitation frequency

Test set-up:
- Connect the +5V to J6, ground to J8, +16V to J7
- Connect parallel port cable from evaluation board to PC
- Make sure jumper is present on J9
- Start MS3110 program for programming the chip (can be started in: *G:\JPE\Control\UniversalCapacityMeasurementIntegration\WERKdir_SW\Software/ MS3110 Pgm.exe*)

Calibration procedure:
- Click on *CHPRST* to reset the chip
- Set R, T, D, B, OFF to *Nominal*, SOFF to *~2.25V*, CSELCT to *0.5KHz*, GAINSEL to *2*, CF to *14.668pF*, CS1 *5.263pF*, CS2 to *0.266pF*.
- Connect multimeter to V2P25 (TP1) and GND (TP7) and measure DCV. Adjust T-register so that voltage is as close 2.25V as possible (+/-0.01V). Press *Write control reg* after each change and observe new voltage on multimeter.
- Disconnect jumper on J9 and use multimeter as ampere meter (DCI) between pins (use white and black hole on multimeter). Adjust R-register to measure a current as close to 10µA as possible. When done remove multimeter and replace jumper on J9.
- Use oscilloscope on bottom pin of J3 (CS2) to measure excitation frequency. Should be trimmed to 100KHz (+/-5KHz).
- Remove oscilloscope and place multimeter on VOUT (TP5) and GND (TP7) and measure DCV again. Voltage should be close to 502mV. Adjust OFF-register to match as close as possible.
- Now adjust CS2 to *0.532pF* and observe new output voltage after pressing *Write control reg*. Voltage should be about 595mV. Differences can be trimmed with the B-register. A present offset when CS2 was set to *0.266pF* should also be remembered when trimming this register.
- Reset CS2 to *0.266pF* again and check if voltage is still close to 502mV, else remodify registers OFF and B.
- If all settings are set and calibrated correctly, press *Write EEPROM*, a message tells you to turn on the +16V supply. Since it is connected already, just click OK and wait until programming is complete. After programming, click *CHPRST* followed by *Read control reg* and check that all the same settings are still present.
- The MS3110 is now calibrated; repeat all the steps above in the same order if another chip has to be calibrated.

APPENDIX C: UCM_01_002 ASSEMBLY INSTRUCTIONS

The assembly of the revised UCM_01_002 print is pretty straight forward, only a few points of attention are required:

- **Prior to assembly, the MS3110 has to be trimmed following the instructions of Appendix B:. Trimming cannot be done anymore once the MS3110 has been soldered on the PCB.**
- The following RS232 components can be omitted when PCB is manufactured for selling it (No additional debug needed):
    - C44, C45, C46, C47, C48, C49,
    - J7, J9
    - U9
    - R24, R26
- RST jumper (J8) does not have to placed, but ISP jumper (J6) should always be present to avoid accidental access to the boot mode.
- JTAG jumper (J1) optional; only needed to flash LPC2129 once.
- Tantalum capacitors have polarity stripe at +.
- Only mount shielding cap U13 if functionality of all components under has been confirmed.
- Dipswitch block S1 should be placed with switch number 1 at the top.
- Software functionality can be confirmed by placing 2 jumpers at J12 over pins 3 & 4 (CAN1H & CAN2H) and over pins 5 & 6 (CAN1L & CAN2L). LED1 should be flashing or lit continuously, depending on sample frequency, after 1 or 2 minutes.
- Electrical contact between elbow BNC connectors and other ground surfaces should be avoided when creating a system with one or more UCM's.
- Do not confuse plus and ground when connecting the power supply. There is no reverse polarity protection present.
- Make sure C50 is at least 220nF. Smaller values can cause a bad reset at power up.
- **Currently shape S1 is a little too wide.** When assembling by hand, solder left pads straight on pins. All the pins on the right side have to be connected to the same net, so they can all be soldered together.

APPENDIX D: UCM_01_002 SOFTWARE INTERACTION

The firmware written for the new UCM (UCM_01_002) will start without any user interaction and run at its default settings, from which a few depend on the jumper settings.

Dipswitch settings:
One block with 8 dipswitches is present on the bottom right of the PCB (S1). Switch number 1 is the switch on top, no matter how the component is placed. A dipswitch is a logic 1 when the switch is moved to the ON side, the other side is a logic 0. With dips 1-8 the following settings can be made prior to system boot:

- Jumper 1-3: UCM ID bit code 0-7, each UCM on one CAN bus should have a unique ID, else error code is transmitted. ID 0 should always be present; else UCM system will not start.
- Jumper 4: Set sample frequency to default (=0) or set by dips 5-8 (=1). UCM system will start with the sample rate defined by dips 5-8. If selected sample frequency by dips 5-8 is undefined, default sample rate is used (=500 Hz).
- Jumper 5-8: Sample frequency to use if dip 4 is 1. The following values can be used:
    - /* Defined sample rates */

/* Defined sample rates */	Dec	Hex	Bin
#define SF_7500Hz	0	0x00	0000
#define SF_3750Hz	1	0x01	0001
#define SF_2000Hz	2	0x02	0010
#define SF_1000Hz	3	0x03	0011
#define SF_500Hz	4	0x04	0100
#define SF_100Hz	5	0x05	0101
#define SF_60Hz	6	0x06	0110
#define SF_50Hz	7	0x07	0111
#define SF_30Hz	8	0x08	1000
#define SF_10Hz	9	0x09	1001
#define SF_5Hz	10	0x0A	1010
#define SF_2P5Hz	11	0x0B	1011

CAN constraints:
Certain parameters can be changed or the system can be restarted by sending some defined commands on the CAN bus while the firmware is running. The other device which is responsible for sending the commands to the UCM over the CAN bus, has to use the same or compatible bus settings. There should also always at least 2 devices be connected on the CAN bus before the UCM is powered on, else a timer will count the number of lost messages and disable the CAN bus when a certain value is met. It is possible to reset the CAN bus again with an external CAN command, since only the transmission part will be disabled on the UCM, not the receiving part.
The CAN bus on the UCM is configured with the following settings:

- Baud rate: 1MBd
- CAN Clock: 12MHz
- Sync jump width: 1 CAN clock
- Delay from nominal sync point to sample point: 9 CAN clocks
- Delay from sample point to next nominal sync point: 2 CAN clocks
- CAN bit time: 1µs

The used CAN cable does not have to be terminated with the typical impedance. Both CAN channels have been terminated properly on the UCM PCB itself by a 60Ω resistor between CAN H/L line and split pin on CAN transceiver. The split pin is connected to ground by a 1nF capacitor.
It is generally recommended, that one CAN device connects its ground to a signal line, but no more than one. The UCM PCB has no pin on the CAN connect header connected to ground, so the user is free to make a ground connection on one of his own devices.
A CAN command to configure one or more UCM's on the same CAN channel should have the same structure as shown in the table below. The action followed by the command is also explained here.

Table 9.1 UCM CAN command list & explanation

Command Define	CAN Message ID	CAN Message Data	UCM action
CAN_RESET_UCM_ID	0x00	Don't care	Lets watchdog timer overflow causing software reset
CAN_NEW_SF_ID	0x01	Bit 0-7: new sample rate Bit 8-15: UCM to change	Same values can be used as with dipswitches 5-8 for sample rate. Set bit 8 to 1 to change sample rate for UCM with ID 0, bit 9 for ID 1, etc. Leaving bits 8-15 all 0 changes the sample rate for all UCM devices connected.
CAN_SYNC_ADC_ID	0x02	Don't care	Sends sync command to ADC. Can be used after sample frequency has been changed to synchronize several ADC's on the same CAN bus.
CAN_RESET_BUS_ID	0x03	Don't care	Resets CAN error counters in UCM and resets CAN bus resuming its operation.
CAN_SET_INPUT_WINDOW_ID	0x04	Bit 0-6: Input range 0.1pF Bit 7: Determines meaning bit 8-15 Bit 8-15: Depends on bit 7 If bit 7 = 1: Low input value in 0.1pF If bit 7 = 0: Sets current input to certain percentage of new range Bit 16-23: UCM to change Set bit 16 to 1 to change input range for UCM with ID 0, bit 17 for ID 1, etc. Leaving bits 16-23 all 0 changes the input range for all UCM devices connected.	New input range is determined by first 7 bits in 0.1pF steps. Minimal value 1 (=0.1pF), maximal value 100 (=10pF). The offset of the new range is determined by bit 7. Is bit 7 equal to one, then bit 8-15 dictate the low input value in 0.1pF steps with a minimum value of 0 (=0pF) and maximum value of 99 (=9.9pF). Is bit 7 equal to 0, then bit 8-15 determine the percentage of which the current input value lies in the new range. Minimal value 0: current input is lowest value, nominal value 50: current input lays half way in new range, maximal value 100: current input is highest value in new range. Sending values out of range will truncate to closest value in range. Defining an input range outside the 0-10pF range also clips to a value inside this range.
CAN_TOGGLE_AIOS_ID	0x05	Bit 0-7: UCM to change Set bit 0 to 1 to change input range for UCM with ID 0, bit 1 for ID 1, etc. Leaving bits 0-7 all 0 changes the input range for all UCM devices connected.	Toggles automatic input-output shaping. UCM will attempt to focus automatic if input is fixed within certain limits by increasing its sensitivity in pF/V or decrease if input is changing outside certain limits. AIOS is switched off default.

LED indicators:
There are two LED's present on the UCM, LED1 and LED2. When the UCM is normally running, LED1 blinks 10ms each time data is transmitted and LED2 blinks 10ms each time a CAN frame is received, except for an ADC data frame.
When the system is starting up, the LED's follow this cycle:

1. System is turned on, both LED's are lit.
2. MS3110 is configured, LED 1 is turned off.
    1. If 2 same ID's are present, LED 1 is lit 10ms each second indefinitely.
3. After 25s LED 2 is also turned off.
4. LED 2 is on indicating system is ready and ADC starts sampling.
5. LED 2 goes off after 5s indicating the start of data frame transmission on the CAN bus.
6. LED 1 is now lit 10ms each time data is transmitted, LED 2 when received, as described above.

APPENDIX E: UCM_01_0011A SCHEMATIC