Non-destructive dynamic motor characterization setup

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BSc Report

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Abstract

The goal of this project is to design and build a motor measurement setup that can characterize a wide range of motors without damaging the motors. To define a scope for the project it is needed to understand a few things: what kind of motors are used, in which situations these motors are used and what parameters are needed to be able to better predict the behavior of these motors.

This setup consists of 2 parts, the load and the motor under test (MUT). This thesis will show the development of the systems around the MUT. This includes the software, the actuators needed to drive the MUT and the sensors that measure direct variables of the motor like: current, voltage and temperature etc. At the end of this project there should be a system that can estimate motor parameters and other motor characteristics that are needed to build an accurate model.

Contents

1 Introduction

Nowadays almost everything is simulated or modeled before it is built, this is also the case in robotics. At the heart of most robotic projects we find electric motors as actuators, to model these motors some parameters are needed. Not all manufacturers supply these parameters or sometimes the manufacturer of the motor is unknown. Either way the best way to determine the parameters is by measuring the motor. The goal of this project is to design and build a motor measurement setup that can characterize a wide range of motors without damaging the motors. This setup is split in to two parts, the active load and everything around the motor under test (MUT). This paper discusses the development of the sensors and parameter estimation of the MUT. A diagram of the system showing the load as a black box and the MUT can be seen in Figure 1.1. To help design such a system the following questions are formed:

1. What parameters characterize a motor?
2. How is a gearbox characterized?
3. How can maxima be estimated without a destructive measurement?

First a literature study and an interview is done to answer these questions. Tools like funkey diagrams and MoSCoW diagrams are used to list the required features and to divide them into subsystems. After the division of subsystems the design and implementation of each of the subsystems is discussed. Then results of the setup will be discussed. At the end there is an conclusion and and some recommendations for further work.

1.1 Earlier work

Morozovsky et al. (2013) published a paper about the development of "An Inexpensive Open Source Dynamometer for Robotics Applications" they called the setup RAPID (reconfigurable automated parameter-identifying dynamometer). It is basically an inertial disk that is brought up to speed by the MUT while measuring various quantities, a labeled drawing of RAPID is shown in Figure 1.2. RAPID is able to determine motor parameters that determine its dynamical behavior. But for this assignment more than only the dynamic behavior is needed.

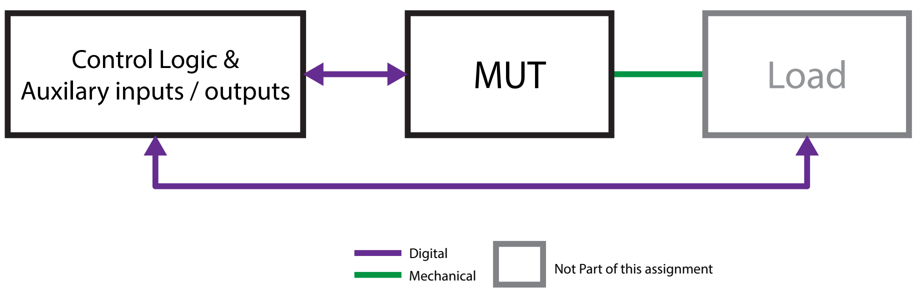

Figure 1.1: The system divided in to two parts: the load and the MUT with control, sensors and actuators.

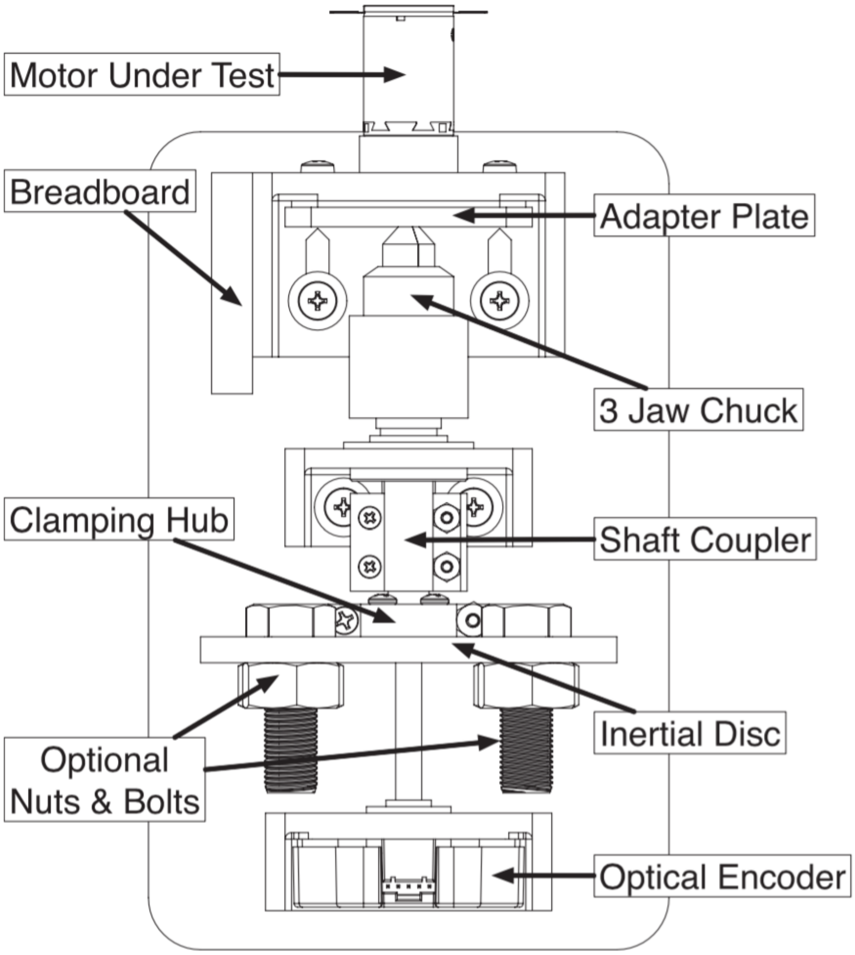

Figure 1.2: Labeled overhead drawing of RAPID assembly.

2 Analysis

This chapter explains which features are required for this system, how the subsystems are formed and why they are needed. These subsystems are connected to a RaMstix, The RaMstix is developed in the Robotics and Mechatronics group here at the University of Twente. Documentation of this board can be found online (Robotics and Mechatronics, University of Twente, Netherlands, 2017). The RaMstix can be used as a 20sim target; 20sim is a simulation and modeling package by Controllab Products (2008). The RaMstix together with 20sim is the basis of the system.

2.1 Questionnaire

A questionnaire was done in the research group to define an operating range for the setup. The written answers can be found in Appendix B. Some interviews were done verbally and unfortunately these are not written down. Based on the written and unwritten interviews an operating range for the system was set tot 0-5000RPM and 0-5Nm, this means that the setup should be able to test motors in this range. The participants were also asked what features they wanted in addition to the RPM-Torque curve which the old setup already could do, key features that resulted from this where:

- Determine motor constant
- Efficiency plot of the motor
- Characterize gearbox efficiency
- Quantify play in gearboxes

These requests where be added to the list of features from the assignment.

2.2 Motor Model

As mentioned earlier the goal of this assignment is to characterize motor parameters, but what parameters determine the characteristics of a motor? In Figure 2.1 a standard model of an DC motor is shown, this model consists of multiple "ideal" components. What can be seen from the model is that there are two time constants: one electrical (the resistance and inductance) and a mechanical (friction and inertia). Besides the time constants there is also a gyrator with a gyration factor that is equal to the motor torque constant. These time constants can be estimated, the electrical with an impedance measurement and the mechanical can be estimated by spinning up and down the MUT.

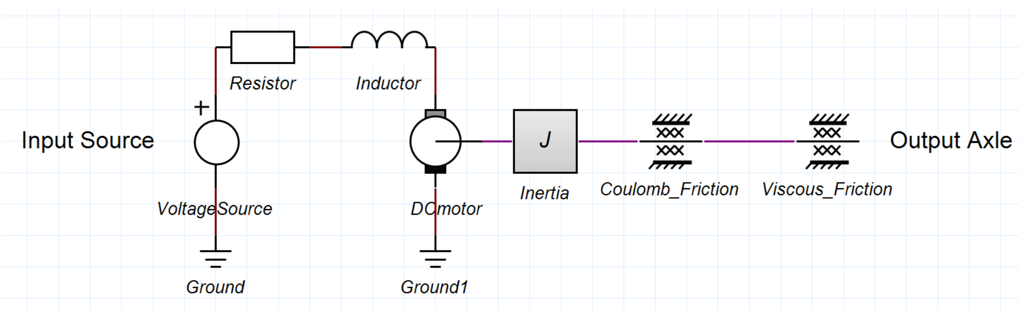

Figure 2.1: Standard ideal physical model of a motor

Functions \ Keydriver	Voltage Measurement	Current Measurement	Motor Control	Temperature Sensors	Torque measurement	Speed Load	Speed MUT
RPM-Torque Curve	x	x	x			x	x
Estimate Impedance	x	x	x				
Estimate Motor Constant		x	x		x		
Estimate Inertia and Friction	x	x	x			x	
Efficiency Curve	x	x	x		x	x	
Drive MUT			x				
Characterize Gearbox efficiency	x	x	x		x	x	
Quantify Gearbox Play			x			x	x
Non-destructive Max Power Estimation	x	x		x			

Figure 2.2: Funkey diagram

Must
- RPM-Torque Curve
- Drive MUT

Should
- Estimate Motor Constant
- Efficiency Curve
- Estimate Impedance

Could
- Characterize Gearbox efficiency
- Quantify Gearbox Play
- Estimate Inertia and Friction
- Non-destructive Max Power Estimation

Won't
- Drive Brushless Motors

Figure 2.3: MoSCoW diagram

2.3 The System

A funkey diagram is used to translate the required functions to subsystems which is shown in Figure 2.2. In Section 2.3.1 to Section 2.3.6 is explained why these functions need the associated subsystems. There is not enough time to realize all of these features therefore a MoSCoW diagram (shown in Figure 2.3) is made to illustrate which of the functions were actually designed and implemented during this assignment. A complete overview of the system with its subsystems is shown in Figure 2.4.

2.3.1 RPM vs. Torque vs. Efficiency vs. Power

A RPM-Torque curve shows the relation between speed and delivered torque; in the ideal case these are inversely proportional. The MUT is spinning without load and gradually a load is applied the motor is slowed down because it needs to deliver torque, do this while measuring the torque and RPM. The RPM-Torque curve is the resulting values plotted against each other. The product of the input voltage and current gives the electrical power at that operating point, this can be added as a function of speed. At last the efficiency can be calculated, this is the product of angular speed and torque. The ratio between the electrical power and the mechanical power is the efficiency of the motor.

2.3.2 Motor Constant

The motor constant is the relation between input current and resulting torque, this can calculated from the same measurement as for the RPM-Torque curve.

$$K_T = \frac{\tau}{I} \tag{2.1}$$

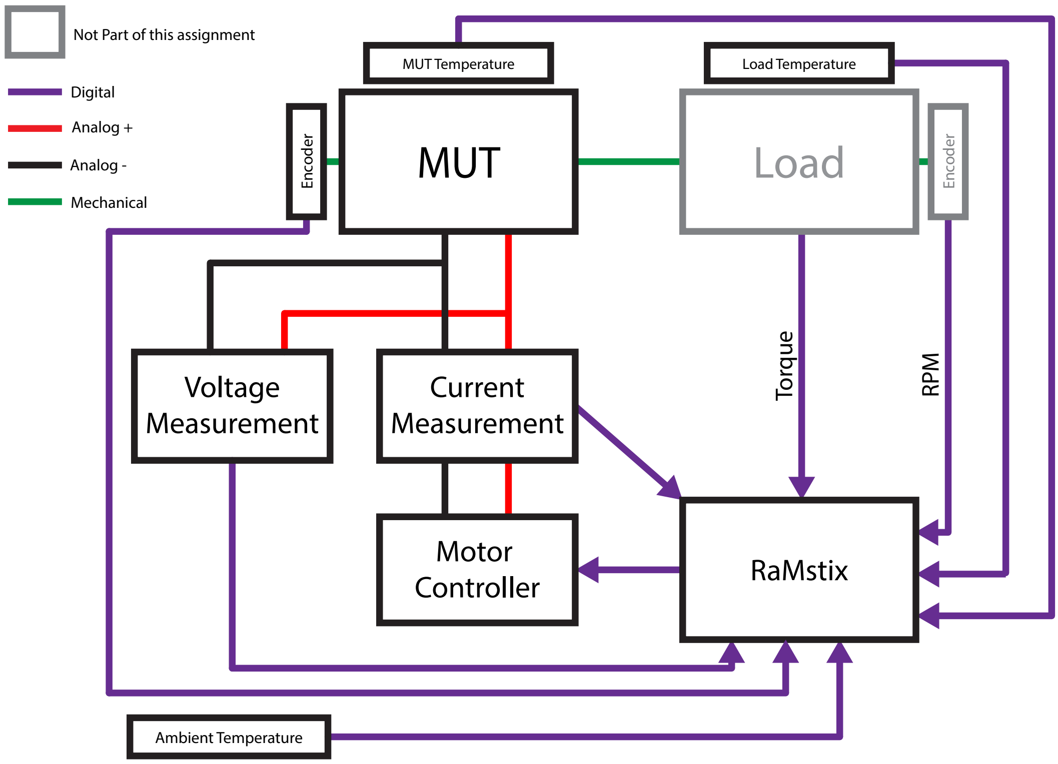

Figure 2.4: System overview

2.3.3 Impedance

The impedance can be calculated if the motor's axle is fixed and a sinusoidal input voltage is applied while the current is measured. The relation between voltage and current for a complex impedance is given in Equation 2.2.

$$Z = \frac{|V|}{|I|} e^{j(\phi_V - \phi_I)} \tag{2.2}$$

The impedance can also be measured with an impulse of step response. For this the motor axle also has to be fixed.

2.3.4 Maximum Power Estimation

The maximum power can be estimated in a few steps; first estimate the winding's thermal capacity and then its thermal resistance to the outside world. Estimating the thermal capacity can be done in the following steps:

1. Fix motor axle
2. Measure the impedance of the motor at room temperature
3. Insert known amount of energy in motor winding
4. Measure the impedance again

With the difference of impedance the temperature difference can be calculated assuming a few things: the winding material should be known or guessed and the fact that the addition of energy is done in a much smaller time than the thermal time constant. Because the added energy is known the thermal capacity can be calculated as well. The impedance measurement

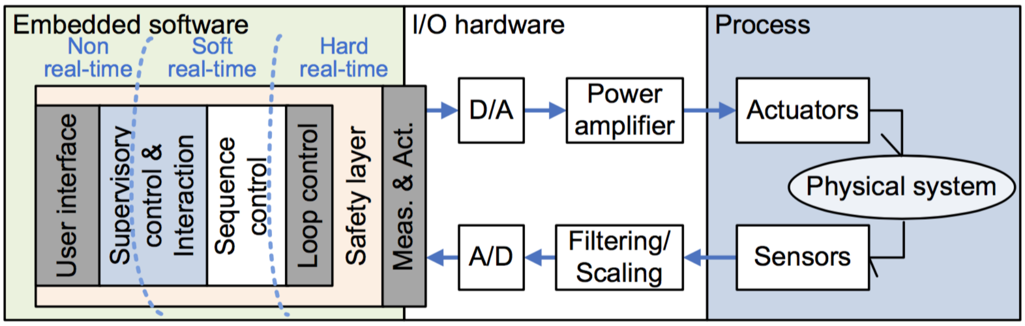

Figure 2.5: Diagram showing the general architecture of robotic control systems.

needs to be repeated multiple times during the cool down period to estimate the thermal time constant. With the time constant and the thermal capacity the windings temperature can be modeled during run time if the input current is know. Because of time limitation this is not implemented.

2.3.5 Gearboxes

If a motor has a detachable gearbox (e.g. Maxon Motors) the efficiency of the gearbox can be calculated if the motor is measured first without gearbox and afterwards with gearbox. The difference in output power is the loss in the gearbox and therefore the efficiency can be calculated. If the motor also had a rotary encoder attached to the motor axle (not the output shaft of the gearbox) also play can be measured if the output axle of the gearbox is fixed. If there is play in the gearbox the shaft can be turned a bit, the encoder of the motor can measure this movement.

2.3.6 Motor Control

The system should be able to shut down the MUT to protect the motor from damage. A simple electronic switch like a mosfet is able to do this, but this limits the system as the motor can only be on or off. For some it is interesting to know how the motor behaves when it operated at less then full power. Therefore the motor controller should be able to control the voltage over the motor this can be done either linearly or with PWM.

2.3.7 20sim

Figure 2.5 shows the general architecture of control used in robotics. This structure is also applied in this project.

3 Subsystem Design and Implementation

In this chapter the design and implementation of the subsystems shown in Figure 2.4 is discussed.

3.1 Current Sensor

The RaMstix had only two analog inputs[1], because the torque sensor and the voltage measurement already use these two inputs a digital sensor or an additional ADC is needed. Off-the-shelf sensors with a digital output were not available. This only leaves two other options a current measurement chip with an digital output or a transducer that produces a voltage proportional to the current and measure that with an ADC. For the transducer there are two types available: inductive sensors or a resistive shunt. The solutions proposed are compared in Table 3.1. The option with a shunt, current sense amplifier and a separate ADC is the best because it has the highest resolution and accuracy in the operating range.

Type	Range	Resolution	Accuracy	Development Time	Bidirectional
Integrated Sensor	16A	9 bits	2%	7 days	No
Hall Sensor	30A	16 bits	2%	4 days	Yes
Shunt Sensor	12.5A	16 bits	1,5%	4 days	Yes

Table 3.1: Decision table comparing different options for the current sensor

The shunt method measures a small voltage (a few tens of mV) over a small resistor (order of mΩ), a special amplifier designed for this purpose is used to amplify this voltage to the full scale input of the ADC. The ADC chosen is the ADS8321 this specific ADC is also on the RaMstix board and therefore chosen as this was supposed to make implementing the readout simpler. The ADC only needs an external voltage reference and a few decoupling capacitors to operate. The design started of with an copy of the ADC's design on the RaMstix board, this includes the ADC and voltage reference of 2.5V. A reference of 2.5V makes the full scale input of the ADC -2.5V to +2.5V-1 LSB, a LSB is $\frac{2V_{REF}}{2^{16}} = 76\mu V$. The voltage at the input of the ADC is a product of the current times the resistance time the gain factor of the current sense amplifier. One thing to consider is the power dissipated in the shunt resistor, Bourns has a series of shunts (the CSS4J series) that have extremely good temperature coefficients and have 2 separate sense contacts such that the high impedance path to the current sense amplifier has less interference form the high current path. The shunts come in 3 values; 2mΩ, 1mΩ and 0.5mΩ. These are all smaller then necessary, the 2mΩ dissipates only 200mW at 10A (the shunt is rated at 4W). To have a full scale of 10A with this shunt and a reference voltage of 2.5V the gain should be $\frac{2,5}{0,002*10} = 125$. The current sense amplifier should have a maximum gain of 125, a lower gain results in a larger input range at the expense of resolution. The INA199 is a current sense amplifier with an extreme low offset and is easy to implement, it also comes in three versions: a gain of 50, 100 or 200. A gain of 100 results in a input range of ±12.5A this is more than needed but suitable for the purpose. As this solution is composed of only 3 IC's (and some passives) it is feasible to design such system on a small printed circuit board (PCB), a schematic is made with these components and are designed according to the reference design of the manufacturers. The resulting schematic and PCB can be found in Appendix A.

[1] Robotics and Mechatronics, University of Twente, Netherlands (2017)

3.1.1 20Sim Interface

There are 2 options to implement the ADS8321 on the RaMstix. The 2 ADC's that are already on the board are connected to the FPGA and have their own hardware for readout, these values than are put in their own registers of the GPMC bus such that the micro-controller can read the values from the bus. The first option is to expand the GPMC bus with a additional address for the third ADC and modify the FPGA that it has extra hardware for the extra ADC. The only thing that needs to be changed on the micro-controller side is to add an extra "chip select". But expanding the GPMC bus involved moving a lot of addresses and this is a time consuming task. The other option is to use the generic SPI bus to connect the ADC to the RaMstix, the ADC has a digital communication protocol that is a hybrid between SPI and SSI. To send and receive data on this SPI bus no VHDL has to be written or adjusted, only some code for the micro-controller and a bit of XML for 20sim needed to be written. In and outputs for a 20Sim target are defined in the .tcf file, this is an XML file that links user select able I/O ports to C-code functions. The XML file needs 3 functions; an initialize function which is run only once at the start, a function that returns an input (or is given an output) and a closing function to properly shut down the I/O port. These functions are written, a brief explanation of the code can be found in Appendix C.

3.1.2 Improve sensitivity

The current sensor currently has a 0.5mΩ shunt resistor which brings the full scale input to ±50A. Replacing the shunt with the 2mΩ will increase the resolution by a factor of 4 and probably will reduce the noise as well. The system can be improved even more with an 4mΩ shunt and the INA199A1 (the version with a gain of 50) decreasing the noise even more. The noise seems to be high frequent and can be filtered out if the sample rate is high enough. But decreasing the noise reduces the need of filtering and because the maximum sample rate of the RaMstix is greatly dependent on the amount of sensors used and is estimated to be around 1kS/s.

3.2 Voltage Sensor

Voltage measurement directly at the poles of the MUT can greatly increase accuracy because the motor control does have a small voltage drop and the leads from the power supply have too high resistance to neglect above a few amperes. To measure only the voltage over the MUT a differential measurement is needed. This can be done in several ways:

1. A voltage divider from the positive side of the motor down to ground assuring a maximum voltage of 5V at the input of the ADC on the RaMstix board which can measure the voltage. This neglects the voltage drop on the negative side of the motor.

2. Use both the positive and negative side of the motor and do a differential measurement. The voltage divider then should not go to ground but to the negative lead of the motor. This would limit the range of the ADC greatly as the voltage at the negative terminal of the motor is in the order of volts, and the voltage at the negative input of the ADC cannot exceed 2.75V [2].

3. An other option is to place a differential amplifier in front of the ADC that scales down the range. The INA143 is a differential instrumentation amplifier with 0.1 times amplification. It accepts an input voltage upto 36V and has a single ended output.

The problem with all of the solutions is that the RaMstix is too slow to measure the PWM signal, the sample rate of the RaMstix is limited at a few kilohertz and the PWM frequency is fixed at 16kHz. Therefore all of the above mentioned solutions need some filtering to get the average voltage over the motor terminals, this can be done either passive or active.

[2]See data sheet of the ADS8321, page 7, figure 3.

3.2.1 Realization

Due to time limitations the voltage measurement has not been built and implemented. For now the voltage is assumed to be a product of the duty cycle and the voltage set on the power supply.

3.3 Motor Controller

There is almost an infinite number of motor controllers all with differant features. The motor controllers for this system only needs to generate a high power PWM output from an input. RaM has pre-made motor controllers that only needs three input signals: 1 for the duty cycle and 2 for the direction. These motor controllers are based on the VNH2SP30-E[3], the operate at a maximum voltage of 16V and are rated up to 30A. Developing a new motor controller or buying a off-the-shelf one would require changing the hardware in the FPGA which could take up several days. Designing a new PCB for a custom motor controller would add even more development time and lead time to manufacture the PCB. Therefore it is decided not to develop a new motor controller although that would make it possible to test motors at voltages higher than 16V.

3.3.1 Connecting the motor controllers

Implementing these motor controllers is quite straightforward, it only requires to have the three input signals from the RaMstix and a power supply between 5.5V-16V.

3.4 Temperature Sensors

Options for the temperature sensors are shown in Table 3.2. The Thermocouple and NTC solution both have a analog output and because there is no ADC available anymore these are impractical. Software for the same ADC as for the current sensor is available but the development of a PCB for both solutions takes too much time. The TMP04 and DS1822+ both have a digital output, the TMP04 has an PWM output; the duty cycle represents the temperature. The DS1822+ uses the 1-wire protocol which requires a bidirectional port which the RaMstix does not have. As the RaMstix already has a duty cycle measurement module the TMP04 is chosen as this solution has the shortest development time. The duty cycle measurement module has an average error of less then 1% which is in the same order as the sensor itself.

Type	Range	Accuracy	Resolution	Development Time	Interface
Thermocouple	−100 °C -250 °C	2 °C	n/a	5 days	Analog
TMP04	−40 °C -150 °C	2 °C	12 bits	1 days	PWM
NTC	0 °C -100 °C	3 °C	n/a	4 days	Analog
DS1822+	−55 °C -125 °C	2 °C	12 bits	4 days	1-Wire

Table 3.2: Decision table comparing different temperature sensors

3.5 20sim Control and Measurement

As mentioned earlier 20sim is used to control the RaMstix and other hardware. 20sim and the RaMstix are mainly used as a data acquisition system. The controls for the load and MUT are defined in the "Control_Sequence" block, see Figure 3.1, furthermore the input values are scaled in the "Input_Scaling" block.

[3]STMicroelectronics (2017)

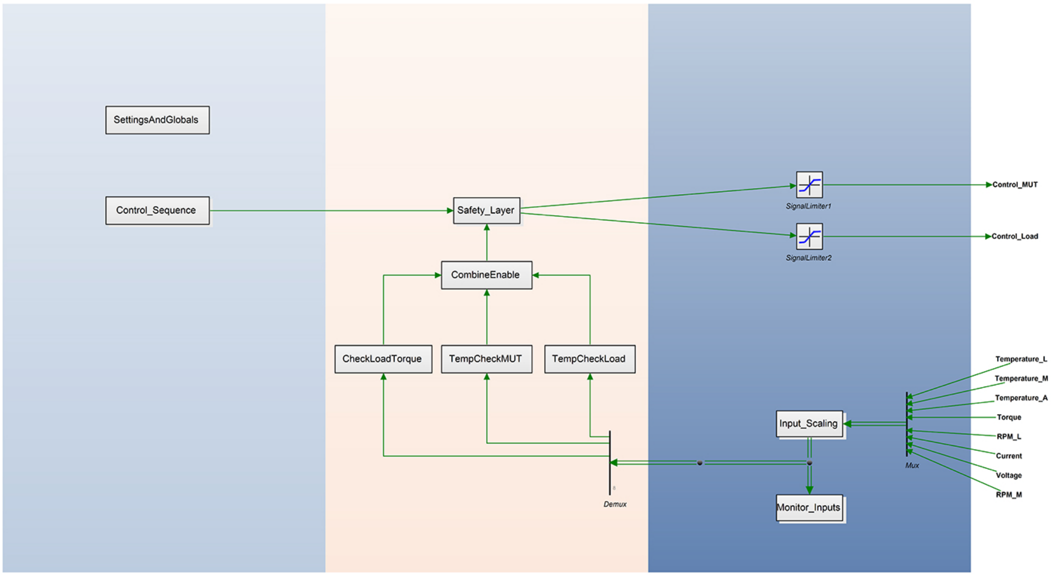

Figure 3.1: 20sim top level overview

3.5.1 Safety Layer

There is a safety layer implemented that disables the output if one of the following conditions is not met:

- $0\,°\mathrm{C} < Temp_{load} < 60\,°\mathrm{C}$
- $0\,°\mathrm{C} < Temp_{MUT} < 60\,°\mathrm{C}$
- $0\,\mathrm{N\,m^{-1}} < Torque_{Load} < 2.5\,\mathrm{N\,m^{-1}}$

This is done to protect the MUT, load motor and load cell.

4 Results

A test run is done, the results are shown in Figure 4.1. The results show some interesting things:

1. As soon as the brake motor (load) starts to brake only a little the current goes up significantly and the RPM drops.

2. At the end the brake motor suddenly fully brakes and stalls the MUT.

3. The load is not 0 when no torque is applied.

This looks like the brake motor goes to 50% power as soon as the output is not 0, and when the output is close to -1 (control range runs from -1 to 1) it jumps to 100% power. But when measuring the input of the H-Bridge it showed a perfect ramp like is supposed to be. Maybe one of the half bridges is broken, this could explain the behavior. That the RPM slowly decreases over time can be explained by the fact that when the temperature of MUT the current goes down, this can also be seen in the graph. At last the offset in the torque sensor can be explained because the wrong offset compensation was used, to correct this 1.534 should be subtracted from each sample.

4.1 Post-processing

20sim is not suitable to do the processing needed to get the parameters or plots needed, because these plots are made with data of multiple time indices. Therefore post processing is need, this can be done in Matlab or any other mathematical tool. Unfortunately there was no time left to build a script to do the post processing for an RPM-Torque graph or to get the motor constant.

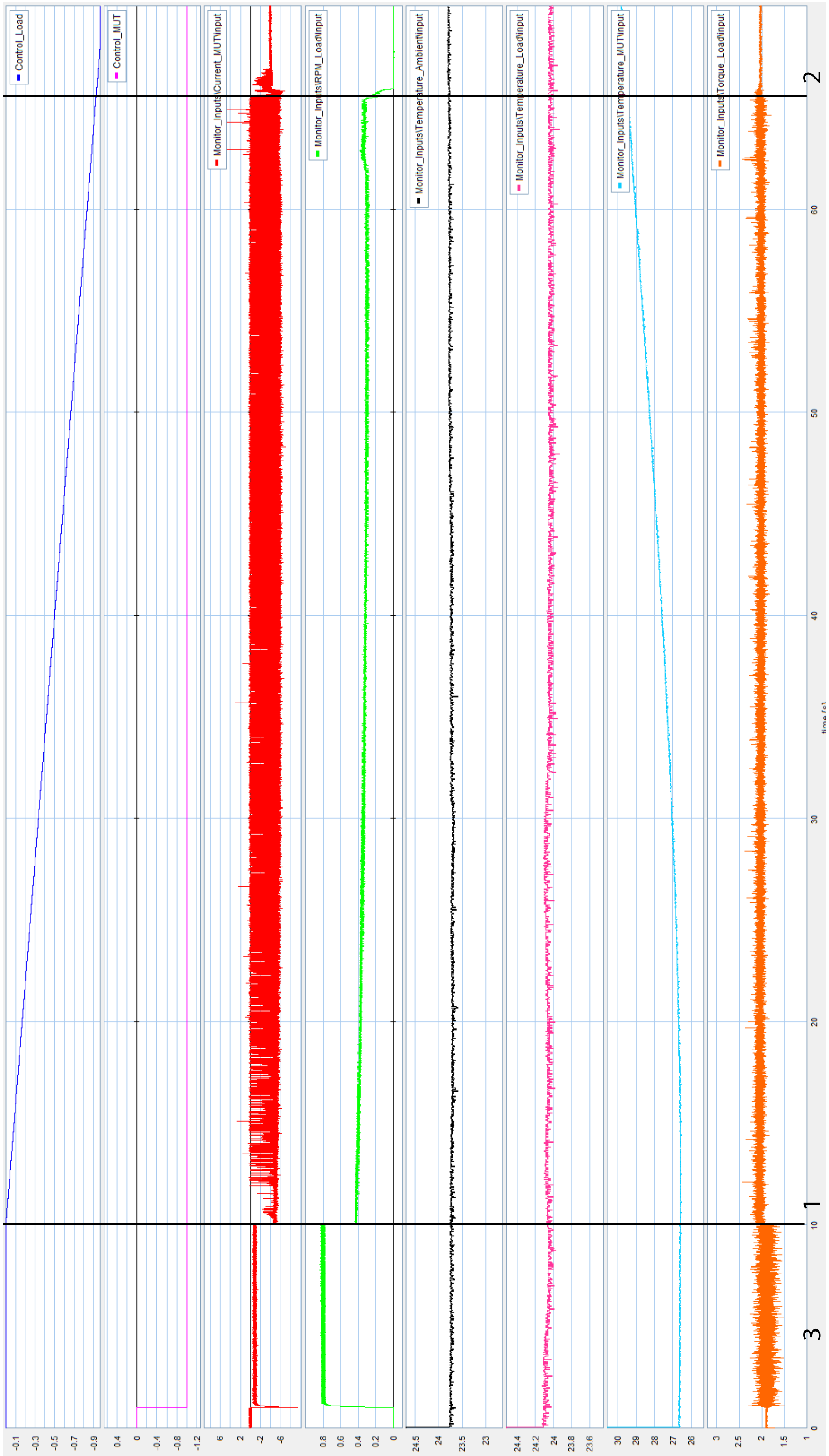

Figure 4.1: A plot in 4C of the obtained data

5 Conclusion

A model of a generic dc motor is discussed and from that parameters that characterize can be found. The characterization of a gearbox is omitted because of the limited time. And a solution for a non-distructive measurement is given, although this is not fully implemented. To conclude, a system to do parameter estimation on DC motors is designed and built, multiple sensors are discussed to realize such a system. There is some unpredicted behavior but if this is fixed and some post processing is done on the data, it is possible to determine: the motor constant, a RPM-Torque graph and a efficiency graph. In Table 5.1 the resulting specs of the system are shown. So it still needs some improvements but it is a good start.

Type	Range	Resolution	LSB	Accuracy
Current Sensor	$\pm 50A$	16 bits	1.5mA	2%
Temperature Sensor	$-40\,°C$ - $150\,°C$	9 bits	0.4 °C	1.5 °C
Motor Control	n/a	11 bits	n/a	n/a

Table 5.1: Final specification table

5.1 Recommendations

The system is not finished, to improve the system a few recommendation are done:

5.1.1 Current Measurement

The sensor shows some drops in current, this is most likely caused by the fact that the bandwidth of the sensor is much higher than the sample rate and the PWM has a frequency of 16kHz. So it samples some samples when the voltage is 0V. This can be solved by adding a small passive filter in front of the ADC or current sense amplifier. Also the sensitivity should be increased as discussed in Section 3.1.2.

5.1.2 Voltage Measurement

This system could be expanded with a voltage measurement to measure to voltage over the motor, this would give a more accurate measurement of the input power.

5.1.3 Impedance Estimation

Because both the voltage and current measurement are not fast enough the impedance cannot be determined via a classical measurement. But an impulse response of step response can be a good solution.

5.1.4 Max Power Estimation

If the impedance estimation works the maximum power estimation can also be implemented.

5.1.5 Integration

But the most important recommendation is to integrate the necessary post-processing and measurement in one system. One option would be: run a web server on the RaMstix with a interface to configure or setup the characterization and display or add an option to download the results when the processing is done. This will make the system much more user friendly and decreases the time needed to preform the characterization. At last support for gearboxes could be added.

A Schematic and Board Layout of the Current Sensor

A.1 Schematic

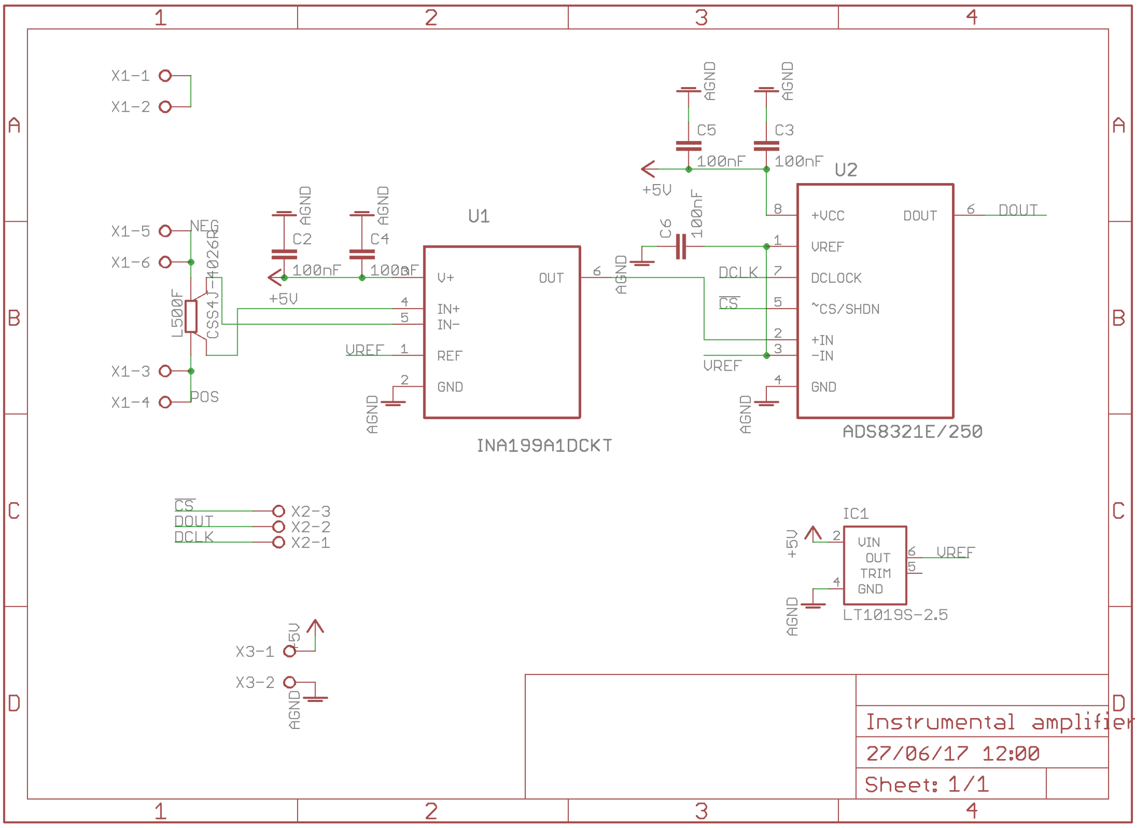

Figure A.1: Schematic of the current sensor

A.2 Board Layout

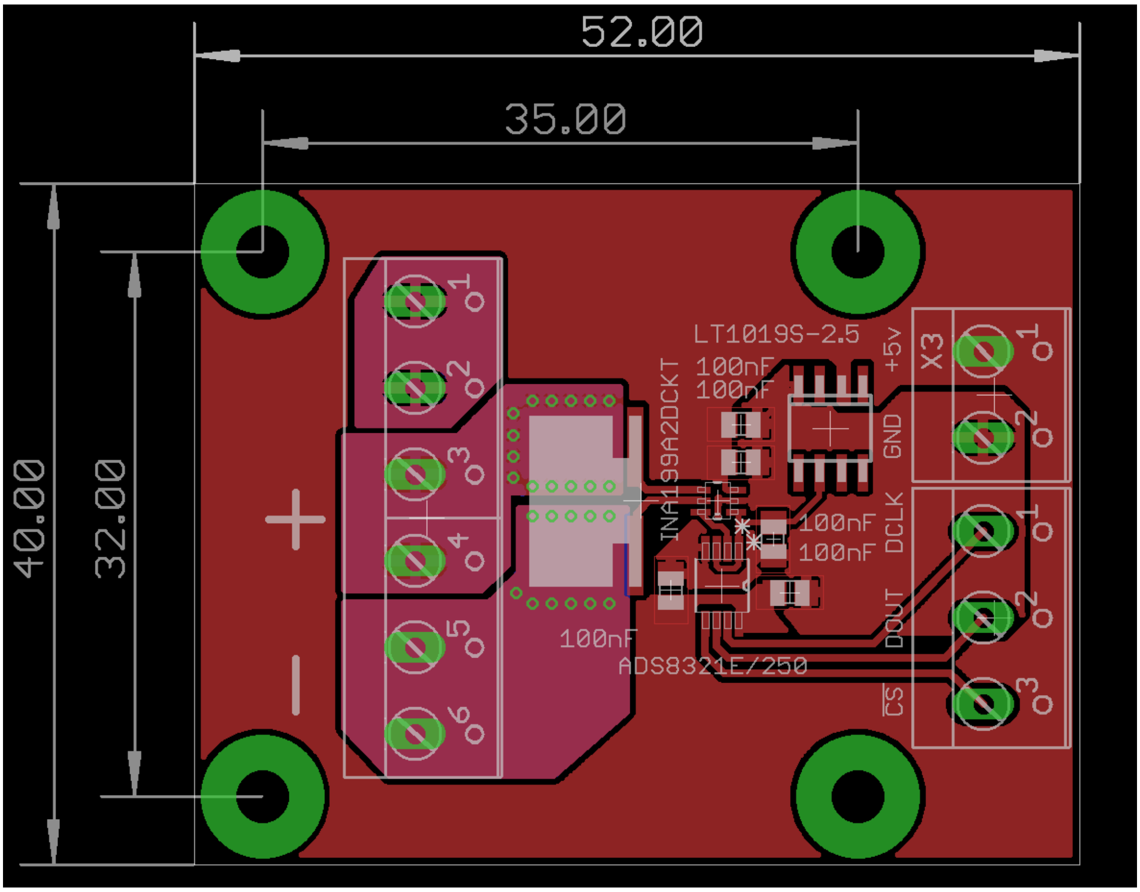

Figure A.2: Printed circuit board for the current sensor

B Interviews

Interviews filled in by people working on RaM projects.

Test setup electro motors

Our BSc. assignment is making a test setup for electro motors for RaM. This test setup will measure parameters which are useful for projects in this chair.

Therefore we have some questions about the electro motors which are used here.

1. Which electro motors are you using? (Preferred are Manufacture names and series names)

For the next questions think about:

- Max. Torque 180 Nm
- Max. speed 400 rpm
- Max. Temperature
- Torque-Speed curve
- Input voltage (AC /DC / pwm)
- Input current

2. Which parameters do you need to get the motor working in your project?

torque / current 'motor constant'

3. Which parameters of a motor are needed to improve the project on which you are working?

Test setup electro motors

Our BSc. assignment is making a test setup for electro motors for RaM. This test setup will measure parameters which are useful for projects in this chair.

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1. Which electro motors are you using? (Preferred are Manufacture names and series names)

Aerolab MT2212 KV750
HS-5~~0~~85MG servo

For the next questions think about:

- Max. Torque
- Max. speed
- Max. Temperature
- Torque-Speed curve
- Input voltage (AC /DC / pwm)
- Input current

2. Which parameters do you need to get the motor working in your project?

Brushless motor drive
Lots of current
no cross conduction
adjustable duty cycle → preferably over a usermade profile

3. Which parameters of a motor are needed to improve the project on which you are working?

ease of use and integration.

FREEQ

Test setup electro motors

Our BSc. assignment is making a test setup for electro motors for RaM. This test setup will measure parameters which are useful for projects in this chair.

Therefore we have some questions about the electro motors which are used here.

1. Which electro motors are you using? (Preferred are Manufacture names and series names)

DC-motor 30:1 Metal Gearmotor 37D-68L mm with CPR Encoder
(manufacture: Pololu)

For the next questions think about:

- Max. Torque
- Max. speed
- Max. Temperature
- Torque-Speed curve
- Input voltage (AC /DC / pwm)
- Input current

2. Which parameters do you need to get the motor working in your project?

* Knowing the right torque is important, because I wanted to simulate it in 20-sim
My motor has 0,776 Nm stall torque
* Max speed is not that important
* Max temp. is not important
* Torque speed curve is important for me!
* I use pwm
* input current is also important for my project
* also I would like to know the most efficient RPM

3. Which parameters of a motor are needed to improve the project on which you are working?

* Efficiency
* Torque

Test setup electro motors

Our BSc. assignment is making a test setup for electro motors for RaM. This test setup will measure parameters which are useful for projects in this chair.

Therefore we have some questions about the electro motors which are used here.

1. Which electro motors are you using? (Preferred are Manufacture names and series names)

Motraxx X-train 4-14 V 10.000 omw/min

Conrad

For the next questions think about:

- ✓ Max. Torque
- ✓ Max. speed
- Max. Temperature
- ✓ Torque-Speed curve
- ✓ Input voltage (AC /DC / pwm)
- ✓ Input current

2. Which parameters do you need to get the motor working in your project?

~~None~~ - input voltage
- motor constant.

3. Which parameters of a motor are needed to improve the project on which you are working?

—

meel schrijven voor
gearbox,
(overbrengingsmodel)

Test setup electro motors

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1. Which electro motors are you using? (Preferred are Manufacture names and series names)

For the next questions think about:

- Max. Torque
- Max. speed
- Max. Temperature
- Torque-Speed curve
- Input voltage (AC /DC / pwm)
- Input current

Brushless ja

2. Which parameters do you need to get the motor working in your project?

Stall metalen voorschriften
5nm
paar 100 rpm

3. Which parameters of a motor are needed to improve the project on which you are working?

C C-Code Driver for Current Sensor

This appendix is a brief explanation of the code written for the ADC.

C.1 Init Sensor

This function is rather small for this ADC as it only requires a clock and a chip select line to operate and does not need any configuration. First the chip select line is set to high (the chip is active low) then the SPI interface is enabled and configured to word lengths of 22 bits and sets a clock speed of 100kHz. The word length is 22 bits because the ADC needs 5 clock cycles to sample the signal value and then 1 clock cycle to determine the first bit after which the 16 bits of data are sent. The ADC can sample at 100kHz if the clock speed is increased to 2.4MHz, but this is not necessary and also not feasible with the FPGA because the delay between setting the chip select line to a value and executing the next line of code is too high. With the clock running at 100kHz the ADC can sample a bit faster than 4kS/s, which is fast enough for now.

C.2 Get Value

To start a conversion the chip select has to be low and a clock has to be present. The clock only is present when the master sends data, this ADC has no data input thus what is sent is not important. After the the master has sent 22 bits of data the sampled data is present on the GPMC bus, which can be read by the micro-controller. Some manipulation is needed to correctly interpreted the data, first the 6 most significant bits do not contain any sensible information. The remaining 16 bits is a two's compliment number, the micro-controller reads it as an unsigned integer and thus needs to be cast to a signed integer. The chip select line can be set high after the data is sent to shut down the chip.

C.3 Close Sensor

When shutting down the system a closing sequence is run. In this sequence the SPI interface is closed and the chip select line is set high in case this is not done already.

C.4 SPI bug

SPI has in total 4 "modes" it which it can operate, it has a positive or negative clock polarity and the data can be valid on the rising or falling edge of the clock (phase). These modes are shown in Figure C.1. According to the data sheet of the ADC it has an positive clock polarity and the data is valid at the rising edge (CPHA=0). But as soon as the SPI is set to this mode the data in the register is not updated anymore. This could be caused by the fact that there is a bug in the hardware description of the SPI interface. Or the documentation of the SPI interface of the RaMstix is not correct and the hardware in the FPGA detects that it is in the wrong mode and maybe therefore it does not update the register. If there is a bug in the hardware, the data of the ADC is sampled at the wrong edge of the clock. Testing the ADC gives the correct values although one would expect random data if it is sampled in the transition region. But the level-shifters isolating the RaMstix and the ADC introduce some delay, this delay may be large enough to still sample sensible data on the wrong edge of the clock.

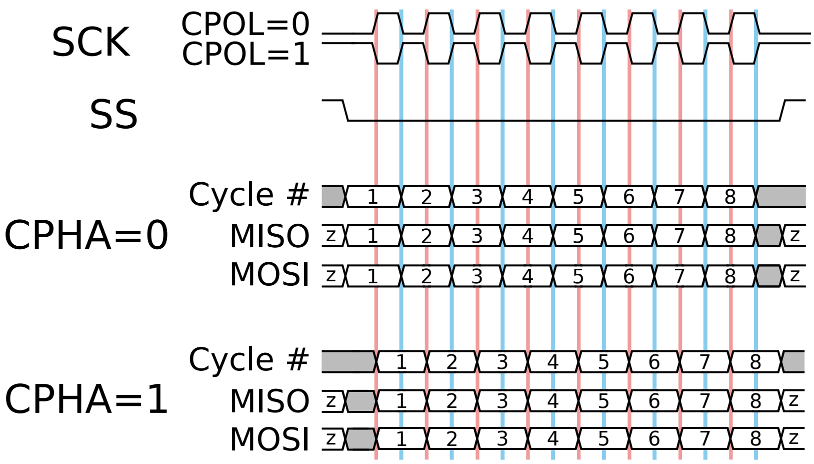

Figure C.1: Timing diagram showing clock polarity and phase, the red line represents CPHA=0 and the blue line CPHA=1

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