Kungliga Tekniska Högskolan

Eco Cars

Elba 2016

Sanel Ferhatovic, Andreas Fröderberg, Emil Hjelm,
Adam Lang, Richard Odell, Alexander Ramm

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Abstract

As the population on earth increases so does the emissions of greenhouse gases to the atmosphere. This has a huge impact on the environment on our planet and there are many incentives to break this trend. Since the automotive industry is one of the main culprits today, a lot of focus is on reducing the amount of emission from vehicles. Shell Eco Marathon is an international event where students are allowed to build vehicles and compete in fuel-efficiency.

This report cover the work on project Elba where a hybrid vehicle was upgraded and modified to run on ethanol. In addition an optimal speed trajectory controller were designed and implemented to minimize energy consumption. A rolling highway, or a test rig, were designed and constructed to be able to test the cars performance on any, simulated, track's height-profile. The theoretical performance was evaluated, which estimated that the car would have a mileage of 197 km/litre ethanol if run on the competition track located in London.

Preface

Without a few key-persons this project would never have been possible, and not as successful. The entire experience has been great and we have learned more than we could ever imagine. We would first and foremost like to thank Mikael Hellgren for being the driving force behind KTH Eco Cars, and also Lei Feng for supervising the project and for making the optimization possible. We would also like to thank Björn Möller for your belief in the project and allowing for a dialogue between the project course and the actual project. The team would also like to thank the other groups within the project who made large contributions to the car before the competition, and managing to almost get the car to complete an attempt. There are more people who also contributed knowledge and helped in one way or another, both from ITRL and the Mechatronics institution. Naturally many people are involved in a big project like this and being a part and directing it is something we will never forget.

Mechatronics team
The bunker
Stockholm, 2016

Contents

Abbreviations

Abbreviation	Description
BLDC	Brushless Direct Current
CAN	Controller Area Network
CEP	Circular Error Probable
DC	Direct Current
GUI	Graphical User Interface
HEV	Hybrid Electrical Vehicle
HTML	Hyper Text Markup Language
ICE	Internal Combustion Engine
ITRL	Integrated Transport Research Lab
MBD	Model Based Development
SEM	Shell Eco-marathon
TLC	Target Language Compiler
UCV	Urban Concept Vehicle

1 Introduction

1.1 Motivation

The development towards greener propulsion systems have played a major part of the automotive industry during the 21st century. There have been numerous incentives to push engineering towards less energy consuming propulsion alternatives. One of these incentives is Shell Eco-marathon (SEM), where university students from all over the world come together to compete in fuel efficiency. Naturally there should be a contribution from KTH and the complexity of the system makes the collaboration between the masters in Mechatronics, Internal Combustion Engine and Machine Design very wise. It also opens for collaborations from other departments such as lightweight constructions. By combining these engineering branches the entire system boundary is covered and there is a good overlap between the programs in the boundary areas. The Mechatronic part of the project is a substantial part, which makes the collaboration between the Advanced Course in Mechatronics and the Integrated Transport Research Lab (ITRL) a really good fit for the project.

1.2 Shell Eco-Marathon

Shell Eco-Marathon is a yearly competition for students to compete with fuel efficient, custom made, vehicles [2]. The competition dates back to 1939 and have been in different locations trough out the years. SEM is split into three regional championships: Europe, Americas and Asia with a World Final for the winners in the different classes. There are two main class divisions, *Prototype* and *UrbanConcept*. There are also sub classes within the main classes based on what fuel/energy type the vehicle uses. Each fuel has an assigned energy value [14] which makes different fuel types comparable.

1.2.1 Urban Concept Vehicle

Elba competes in the UrbanConcept class and is what is called a UrbanConcept Vehicle (UCV). The vehicles in this class have an appearance closer to today's production type passenger cars. The cars in the class have to be built in accordance with the class specific rules that dictates everything from steering and controls to propulsion and safety. UCVs must have some common production car features as wind shield wiper, turn signals, horn, headlights etc. Vehicles competing in this group are also required to "stop and go" each lap, which means that once every lap the vehicle needs to do a full stop. This is to further increase the resemblance to city driving.

1.2.2 London Track

All vehicles drive the same amount of laps, 8 in 2016([15]), which equals 17.9 kilometres. Compared to earlier tracks the London track has a steeper height profile. To climb the steepest part of the track the vehicles must deliver larger amounts of torque than previous years (this is true for Elba). The height profile of the track can be seen in Figure 1.1.

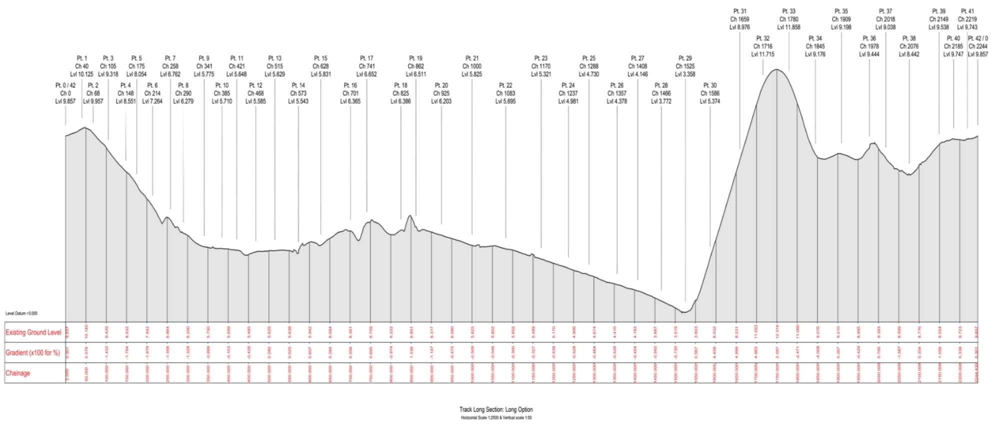


Figure 1.1: Height profile of the London track.

1.2.3 Inspections

Before any vehicle is allowed on the track it must first pass two inspections, the safety inspection and the technical inspection. The safety inspection covers issues related to the safety of the driver, personnel and surrounding cars. The technical inspection covers how the vehicle complies to the rules, specifically energy usage. This ensures that the car does not use power from the auxiliary power source to propel the vehicle in any way.

Simply passing these inspections is not something that teams take lightly and it can be the main goal for many of the teams attending SEM. This means that if the car does not change year-to-year it is often easier to get the car to race the next year.

1.3 Purpose

If one wishes to perform well in Shell Eco-Marathon optimising the speed the car should have on the track could improve performance. This is also something that is interesting for the industry and is not use in current cars when using cruise control. This could both save money and the environment due to the reduced fuel consumption.

One goal the optimisation is to improve result at SEM. Therefore a car, in competition shape, has to be maintained. The car has to be updated to comply whit the current SEM-rules and also simply to be cemt in a drivable state. The car is also seen as a platform for students to test ideas and perform research. Various parts of the car have already been developed as bachelors thesis's and the optimisation will be improved as a part of a master thesis. The car enables students to try to solve both complex construction and design tasks, such as the unique clutch or the laminate door, and experiment with different optimisation strategies in a real world case. Appearing and performing well with the car is the main way to get sponsorship deals to support the project, both with parts and with money to cover travel and transportation costs.

But to be able to do all this test has to be carried out with as little overhead (time, track, transportation etc.) as possible. Also the actual competition track is located in London (and it only exists during the event), so there is no option to go there and test. This is the motivation behind the testrig. Other teams competing in SEM uses these machines to test the car while standing still, but KTH EcoCars had no machine like this. The testrig solves several practical issues for KTH EcoCars and is therefore not only beneficial for the car that was worked on. Several problems had to be solved for it to work: it must supply the torque demanded, is must simulate the forces the car is exposed to, and is has to handle supply of energy and regenerated energy created when braking the car.

1.4 Requirement engineering

In a complex system, there are many stakeholders, both internal and external. The requirements are meant to capture the needs of the users and convey them to the developers [7]. It is important that the requirements are unambiguous [7, 13] in order for there to be no room for interpretation. Since natural language is ambiguous by nature, there are standardized frameworks and templates to improve the quality of the requirements [13].

1.4.1 User and system requirements

Requirements can be organized into two categories, User and System requirements. These differ in a number of ways, both in their nature and how they are procured. A project design often starts with a demand or need from a customer or user. These needs can be seen as the goal for the project to fulfil and are of a high level, abstract nature. They are captured from the users of the system and are expressed in the users language. In essence, the User requirements describe the problem that is to be solved by the system [7].

When the User requirements are set, these need to be condensed into technical requirements that the developers can work towards, these are the System requirements. They define what the system and its sub-systems is supposed to do an it is the developers that own these requirements. They are therefore also responsible for that these in turn fulfill the User requirements [7].

1.4.2 Requirement formulation

As described in Section 1.4.1, it is important that requirements are clear and unambiguous. By using standardized templates when expressing the requirements, there is a framework where it is clear an unanimous what a word or phrase means. This greatly increases the quality of the requirements[13]. By using a template for the structure of a requirement, it is ensured that all parts needed are in the requirement. Rupp [13] gives a template on how to formulate a requirement, which can be seen in Figure 1.2.

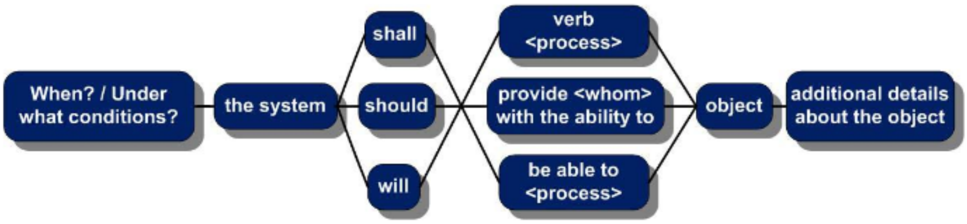


Figure 1.2: Requirement formulation template.

It is also important to realize that in a complex system, there are many relationships between stakeholders and requirements [7]. A change in one requirement may affect several other requirements. Therefore, it is important to have a requirement software that makes it easy to track the dependencies between the different requirements.

1.4.3 Requirements Engineering system

When evaluating which software to use to store the requirements, special requirements are made for how this software should work. It is important to have traceability, both between requirements and to who has made changes, and it is also important that the system is easy to use. Everyone in the team has used IBM Rational Doors for requirements engineering in a previous course, but have all found it cumbersome to use and too packed with features for what is needed for the project. Since only a core set of features is needed, an alternative path is taken. A language such as Hyper Text Markup Language, or HTML, has document layout built in and also allows for easy linking within the document (or webpage). An HTML document therefore allows making requirement documents with traceability. To make the syntax of writing new requirements easier, a Markdown parser is used. Markdown (`http://daringfireball.net/projects/markdown/`) is a simple text-based language that is parsed into an HTML document that can be viewed either in a browser or as a PDF document.

To make writing new requirements easier, a simple webpage that can be run locally on any computer is written. The webpage has input boxes where entries such as requirement name and dependencies can be entered. The data from the boxes is then parsed with Javascript to create a standardized requirement that can be copied and pasted into the requirements document. The layout of the requirement generator webpage is displayed in Figure 1.3.

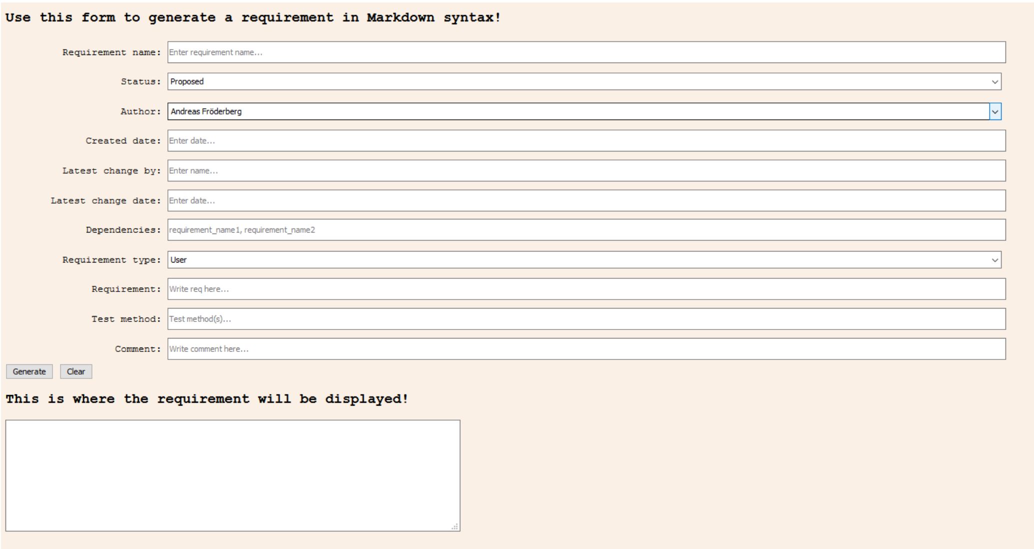


Figure 1.3: Requirement generator webpage.

Having a standardized way of writing the requirements reduces the risk for syntax errors and the added abstraction allows the user to focus on the content. Some automation is also built in to the system, such as automatically adding creation date and having a drop-down menu with team member names. Basing the requirements system on HTML also allows all features of HTML to be added as needed, creating an extensible platform that can be built upon. Should there be a need, Javascript could be added to the requirement document, adding dynamic features such as buttons, automatic dependency detection and much more.

1.5 Design Decisions

When developing a product there might be multiple solutions to a problem, where the solutions might (or might not) fulfil relevant requirements. The entire team where involved in subgroup decisions which meant they had to motivate the different alternatives before one was chosen. These decisions all related to the car and the competition, so they had to follow the cars requirements derived from the rules.

Decisions also had to made for the optimization and the testrig.

2 | Elba The Car

2.1 Introduction

Elba is the name of one of the two cars of the Eco Cars project housed by ITRL. Elba is an Urban Concept Vehicle (UCV) and have been a continuous project ongoing for many years. The design and propulsion system, along with the name of the UCV of Eco Cars have changed over the years and Elba is the name of the current active car. In difference to a couple of years ago when Elba was purely driven by an electric motor, Elba is today propelled by a parallel electric-ethanol hybrid. The platform has been continuously improved and altered to become the complex hybrid that exist today. The goal of Elba is to participate in the Shell Eco-marathon.

2.1.1 Propulsion

Elba combines two electrical motors and one internal combustion engine (ICE). The electrical motors are one 200 W direct current (DC) motor connected directly to the drive shaft and one 1.1 kW brushless DC motor (BLDC) connected via the clutch to the drive shaft. The one-cylinder four-stroke ethanol powered ICE is connected to the drive shaft via the clutch. These three provide a driving torque to the rear drive shaft. The drive shaft is then connected to the right rear wheel via an 1:10 ratio planetary gear. The car fits a single human and he or she is also the driver. The driver steers the car manually and decides upon a reference speed that the car should follow and has the option to decide what motor/engine combination that should be used at a specific time.

2.1.2 State at start of project

The car was in working condition when the project started, but had several problems, including that the clutch was slow and unreliable, the overall power output might not have been enough to be efficient on the new track, none of the potential drivers would fit in the driver compartment and the horn disturbed the entire electrical system. These issues where, together with the competition rules, the primary base for the decisions that where taken and related to the car. Some of the work done to correct these problems where a matter of reshaping some metal piece and bolting it back in the car so that the driver could reach the brakes, while other required an entire team of people to get a new, working, ethanol engine in the car.

2.2 System Overview

2.2.1 Electronic Control Units

The car has four electronic control units (ECUs) that are responsible for controlling different parts of the car. An overview of the communication between the ECUs can be seen in Figure 2.1

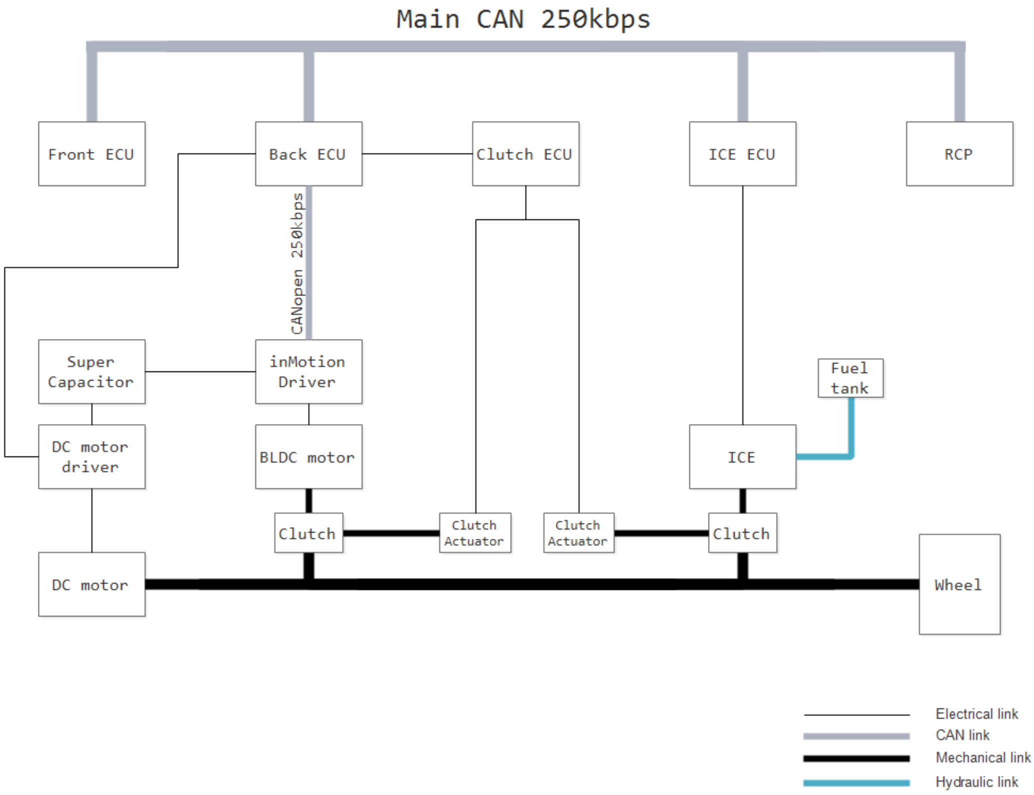


Figure 2.1: Overview of the communication system and drivetrain in Elba

The Front ECU is responsible for the human user interface, which is the

buttons where the driver is able to decide drive mode and reference speed if the car is in manual mode. It transmits speed and drive mode on the CAN bus.
The Back ECU controls the two motors via separate motor controllers. It has veto over the ICE and Clutch.
The internal combustion engine is controlled by the ICE ECU and this is its sole purpose, it does nothing else. It reads the lambda sensor and motor temperature sensors to control the fuel injection.
The Clutch ECU controls the clutch, and it interfaces to two H-bridges which in turn steers the linear actuators.

2.2.2 Communication

The car uses a CAN network to communicate between the distributed micro-controllers. Any data that is needed elsewhere is sent on the CAN-bus. Each CAN message consists of a CAN id, a 32 bit upper data integer and a 32 bit lower data integer.

Messages sent from Front ECU are sent with id 170, from Back ECU with id 169 and 113, and from ICE ECU with id 114. GPS data from the data-logger/GPS-unit Race Capture Pro are sent with id 180. Data position in the messages on the CAN-bus can be seen in table 2.1, counting the least significant bit as bit 1. The lower data accounts for bit position 1–32 and upper data 33–64.

Table 2.1: Data position in different CAN messages on the CAN bus.

Data	Id	Bits
Reference Speed	170	1–16
Brake	170	17
Reference Mode	170	20–23
Auto	170	24
Current Speed	169	1–16
Supercapacitor Voltage	169	17–32
Current Mode	169	33–36
BLDC motor current	169	37–48
Distance	169	49–64
ICE RPM	114	1–16
ICE on/off	113	1–2
Fuel injection time	114	17–32
GPS longitude	180	1–32
GPS latitude	180	33–64

Another CAN network is used between the Back-ECU and the inMotion driver that controls the BLDC motor. This network uses the protocol CANopen that lies on top of the CAN bus. The instrumentation panel communicates via Bluetooth with the Race Capture Pro 2 (RCP2).

2.2.3 Energy supply

All energy used to propel the car forwards (during the competition) comes from the ethanol fuel, but electrical energy can be stored in the super-capacitor. When the electrical motors generate energy it can be stored in this super-capacitor for later use. The car can only start from standstill using one of the electrical motors with energy from the super-capacitor.

2.3 Software and Simulation Models

Using Model Based Development (MBD), relies on verified systems models on various levels. Elba benefits form a full system model to simulate fuel efficiency and each ECU have a corresponding Simulink model from which all code is compiled.

2.3.1 Plant Model

The Simulink plant model is supposed to be a full system model capable of estimating fuel consumption over an entire SEM attempt. When any component, which has an effect on propulsion, is changed on the car the plant model must also be updated. Naturally the goal with MBD is that any change can be simulated with the plant model, approved and then the car is updated. But not all simulations can be done beforehand, which was the case for the new ICE.

The plant model is functionally very similar to the old model described in [12]. The structure of the model was improved to give a clearer view, a way of including the track profile was added and errors in some models were corrected. Also, the work of [8] was included in the form of a reference speed lookup table. The plant model also includes a model of the testrig to simulate forces and torques it is required to output.

Since the new ICE couldn't be properly mapped, the plant model uses parameters from the old ICE. This needs to be considered when interpreting results from simulations on the plant model.

2.3.2 ECU software

All ECUs use Arduino (Due or Mega) micro-controllers, which Simulink has compiler support for. This means that Simulink models can be compiled and uploaded to the Arduino directly from Simulink. The Simulink to Arduino coupling also gives the option of running "external mode" a Hardware in the loop type compile mode. This makes it possible to look at values and signals, running on the ECU, in real-time.

2.4 Data logging

The need for collecting data is a very important aspect when it comes to iteration during the development of the car. In order to determine if changes make the car perform and handle better there is a real need for comparing data. In Elbas case, logging data from multiple ECU's is a must in order to have a complete picture of the car. The absolute best way to log all the relevant data is to log the CAN-bus. All the information sent on CAN is relevant and of highest interest. There was always the possibility of having the laptop in the car while driving but this didn't seem to be the best way. After experimenting with different solutions, including making our own logging device, was the Race Capture Pro 2 (RCP2) found to meet the requirements, see Appendix C. It has the possibility to communicate with two CAN-channels and logging different custom identifiers as virtual channels. With it's eight analogue input channels and three digital I/O channels it is also very suitable for logging both analogue and digital signals, which is a really good addition.

2.4.1 RaceCapture Pro 2

The RCP2 is a customizable lap timer, data logger and telemetry system designed for racing cars. The RCP2 comes with a software GUI that is used for configuration and this software also holds the interface for scripting configurations. The language used in the RCP2 is Lua and this can used to configure everything in the RCP2. One of the two CAN channels of the RCP2 is connected to the main CAN-bus of Elba, as can be seen in Figure 2.1. The main purpose of the RCP2 is to log data, both data communicated on the CAN bus and the GPS-position from the dongle that was provided. To be able to log the custom CAN-bus, there is a function called virtual channels, this allows for customized CAN id's to be logged. There is currently three different virtual channels that have been set up lo log messages sent from the back, front and ICE ECU. These three virtual channels is logging messages with ID 114, 169 and 170, and what is sent with these messages can be seen in Table 2.1. Besides the logging function, the RCP2 is used to track Elbas position on the track. This is done by a GPS-dongle that was provided with the RCP2 and have the following specifications,

$$CEP = 2.5\text{m} \tag{2.1}$$

$$R_{sample} = 50\text{Hz}. \tag{2.2}$$

More on how the GPS signal is used to position Elba on the track can be found in Section 3.4.
The logging file that the RCP2 produces is a Comma Seperated Value file, even though the file format is not standardized, there is a wide spread when it comes to log-files, database information, serial data streams etc. The file format is very convenient for usage with MATLAB, as there are built in functions to load the CSV file and extracting information can be done with minimal effort. During the project a MATLAB script have been developed to both extract the right information and plot the interesting data. The exact way the RCP2 loggs data can be found at [1]

2.5 Requirements

All vehicles at Shell Eco Marathon must pass two inspections before the vehicle is allowed to enter the track. The first a safety inspection evaluating if it's dangerous to have the vehicle on the track, both for the driver and other vehicles. The second is a technical inspection asserting if the vehicle complies with the competition rules and regulations. These two inspections have been the requirements for Elba and a lot of work have been conducted in order to make sure that these have been fulfilled. The requirements have been something that each respective subgroup have worked with to ensure compliance at all levels. The requirements bellow is those that have been relevant for the current project to work with. Requirements that have been decided by prior teams have not been considered to the same extent since many of the vehicle design requirements etc.

2.6 Design decisions

2.6.1 Clutch decisions

One of the major problems with the car have been the clutch. Figure 2.2 illustrates the mechanical components of the drivetrain of Elba.

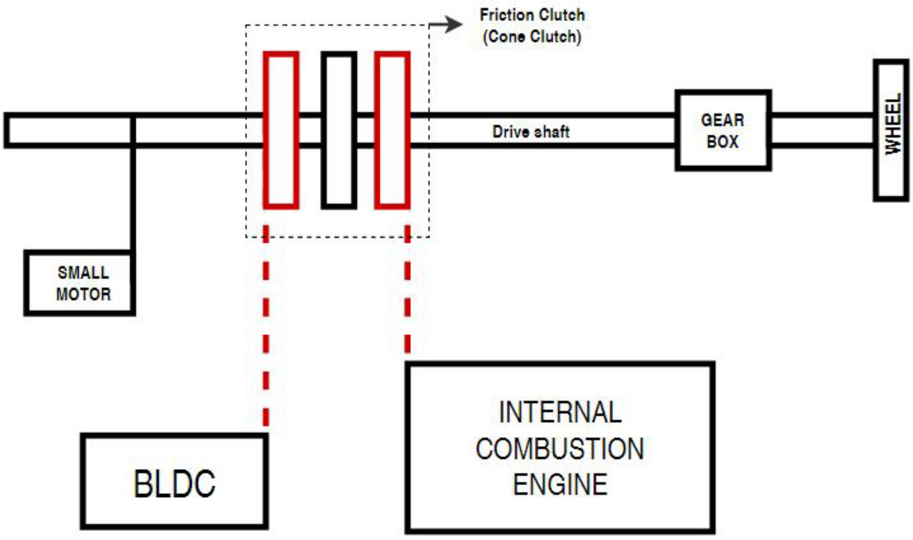
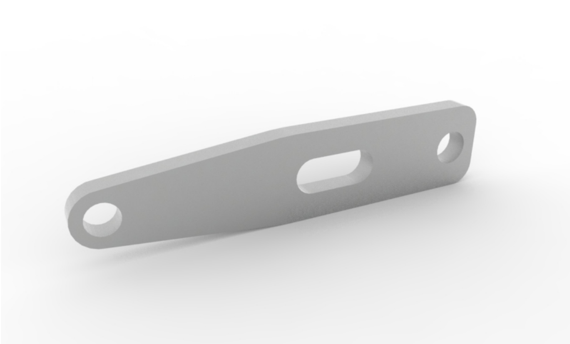


Figure 2.2: Illustration of the mechanical components of the drive train, where the red plates can move towards the center plate to engage and disengage the motors to the drive shaft.

At the start of the project, the problem was that the clutch actuators were oversized and thus giving more force than necessary for the clutch to engage properly. When the clutch was engaged, there was too much actuator force, and so the clutch plate on the ICE side got stuck center plate and could not be disengaged using the actuator.

To solve the mechanical problems it was decided to appoint one team from the machine design department to work solely on the mechanical parts of the clutch. The Mechatronics team decided to completely remake the clutch ECU to make it more robust. Despite the new ECU and the work performed by the machine design team, which can be read about in Appendix [6], there was problems with the clutch when it was time to race. The problems was of the same mechanical nature as before the rework, where the clutch plate on the ICE side could not be disengaged from the drive train. To solve this problem, several solutions have been investigated. The clutch mechanism has been controlled by time rather than position. One approach was to use the built in hall sensor in the actuator to control the position. One other idea was to use an external current sensor on the clutch ECU to control the position. A third idea was to continue using time as reference, but increase it so that an end position is always reached, which can be used as a reference position.

When investigating alternative three, using longer time to engage and disengage the clutch, a new problem was discovered. It appeared that even though the clutch was not stuck to the center plate it still could not be properly disengaged. This was due to the geometry of the lever arm which pushes the clutch plate. After this important insight the drive train was disassembled and new lever arms were constructed and manufactured. When the drive train was assembled again the clutch worked like expected. Figure 2.3a and 2.3b shows both the new and old lever arms.



(a) The new clutch lever arms

(b) The old clutch lever arms

Figure 2.3: This image shows the difference between the old and the new lever arms that are used to push the clutch plates.

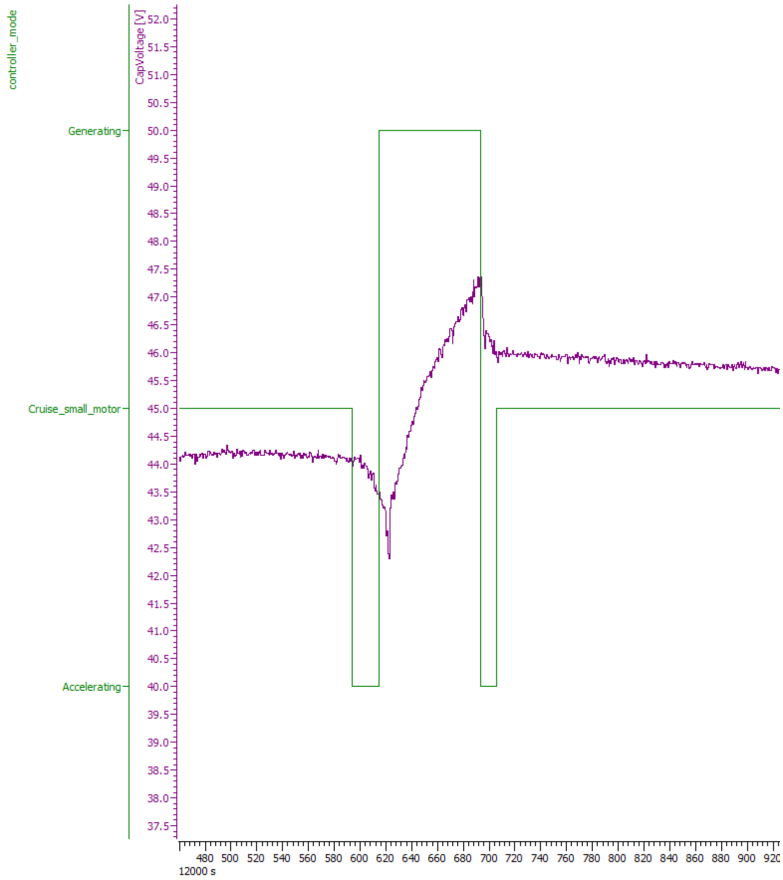


Figure 2.4: Capacitor voltage and drivemode as a function of time

Figure 2.4 illustrates a sequence from CANoe where the capacitor is charged by changing mode from the small DC motor when the voltage is low and charging to a higher voltage level then changing back to the small DC motor.

2.6.2 Internal Combustion Engine and ICE ECU

One of the requirements from the ICE-department was that the ICE should be run on ethanol. An engine running on ethanol needs to have a higher compression ratio than a petrol engine [3, p.8]. The requirements engineering and modifications on the new ICE was set by the ICE team based on the requirement given in the rules, along with recommendations from previous year.

It had been said that last years ICE where too powerful, when the car regenerated its maximum energy at the average track speed the car still wanted to accelerate. Going faster than required saves time but is a waste of energy and therefore bad at SEM. A new ICE was proposed with 50 cc compared to earlier 57 cc. Another major difference was that the new motor had an horizontal output shaft compared a vertical one. This meant that no bevel gear had to be used, which was a major point of failure earlier. The ICE had to be shipped relatively fast and a requirement from ICE-group supervisor was that 3 identical engines had to be bought. This limited the choice even further. Which motor that was chosen in the end and why is motivated in greater detail in appended paper [3].

To control the new engine, a new ICE ECU was needed. It was also decided that the new ICE ECU would contain more sensor inputs as well as the possibility to control the ICE ignition. All functionality of the old ICE ECU would still be present, namely:

- Simulink TLC software.
- Feedback control loop of injection time.
- Lambda value sensing.
- Encoder reading with index pulse from ICE.

More sensor data together with ignition control would give possibilities for more exact control of the ICE. The extra features of the new ECU were:

- Motor oil temperature sensing.
- Ambient air temperature sensing.
- Ignition control.

The features were implemented on the ECU PCB and the system was designed so that the sensors and features could be implemented incrementally according to the time and need of the project. Given that the amount of time that would be needed to get the car in working condition before the race was not easily planned beforehand, it was beneficial to have a base functionality with flexibility to add features.

2.6.3 Door

The car is required to have a door, with a large enough entrance and working locking mechanism [14]. Since the old, layered carbon fibre door was too flimsy and also back hinged (there is a reason its called “suicide door”), it was decided a new, sturdier, door would be made. Two lightweight-construction student took this upon them self as a bachelors project.

The new door where constructed in a carbon fibre sandwich style and was open in a scissor manner. The door became sturdier but the hinges where less than ideal and the closing mechanism did not work.

2.7 Results

2.7.1 Competition

At the time the team arrived in London the ICE had never been started with only ethanol as fuel, the door had to be mounted and the team needed to do a number of small changes to be able to pass both inspections. Most time was spent to get the engine running, but it was never able to run for more than a couple of strokes.

Both the technical inspection and safety inspection were passed. There where a few complaints: The doors closing mechanism was insufficient, the indicator lights were to weak, and the fire-extinguishers expirations date had passed. All these had to be reinspected before Elba was given a pass.

It was decided that one attempt should be made even if the engine never had been started properly. Since the car must be rolling to start the ICE the inertia of the car will keep the ICE turning even if it misfires (the wheel inertia is not enough for this). This meant that the ICE started once the car finally was running during the attempt. At the compulsory stop after one lap the clutch to the ICE did not properly disengage, causing Elba to stall the engine with clutch engaged. While trying to get going again the clutch could not be disengaged and the attempt had to be aborted.

Therefore Elba never got a competition result.

2.7.2 End of project

A lot has happened with Elba since the competition in June. At the end of this project the car is finally in fully working condition. Both the clutch and the ICE which were the major problems have been fixed to a point where they work sufficiency, but not optimal. For the ICE it would be needed to study the engine parameters to make it run more efficiently. The clutch is very slow and would be much more energy efficient if it could engage and disengage much faster. One way could be to study the actuator timings and decrease the distance that the actuator moves, but still keep the proper functionality.

3 | Optimization

3.1 Introduction

The main goal of the project is to have the car consume the least amount of fuel possible. Ideally, the engines and motors should always operate within a certain range of their optimal point of operation. This should be considered when deciding which mode and what reference speed the car should keep in order to reduce fuel consumption. In addition to this goal, there is a number of constraints that needs to be considered in addition to the generic fuel consumption optimization. Things like track topography, super-capacitor voltage and time and distance until finish will all weight in on the output request. The optimization algorithm used in Elbas automatic drive mode was developed as a part of a Master Thesis [8]. The control architecture for this optimization consists of two or three layers and the thesis have completed the top layer speed reference control. This chapter will cover the decentralized hierarchical predictive control that is used to calculate the speed trajectory and it's implementation.

3.2 Design Decisions

The need for an optimization can seem obvious in order to lower fuel consumption. However, depending on the tracks topography there might be other areas that would need much more consideration and things like weight, frontal area and rolling friction might have a greater impact in some cases. In recent years the track of SEM has been more or less flat, with only minor deviations in altitude. With the previous tracks, the considerations for an automated drive mode would more or less only consist of making sure that the voltage level of the super capacitor is within it's boundaries. This means that the ICE needs to be started when the voltage level gets too low and regenerate energy into the super capacitor. Once SEM moved to London, where the altitude changes of the track is much more significant, the conditions became different. On top of the voltage level of the super capacitor there is also room for optimizing the torque requests so that the most efficient propulsion constellation is active at all times. It is also necessary to time the accessible energy so that there is enough energy in the super capacitor in beginning of an uphill, the possibility to regenerate from driving downhill etc. all added to the complexity of the optimization. These new levels of complexity makes the optimization become more of an factor then previous years, and in so there was a collaboration with a master thesis student who used Elba as an experiment in the thesis [8].

The Simulink lookup table that was produced from [8] was dependent on the distance travelled on the track and in so there was a need to get an accurate position reading. There were two options, to get a GPS-positioning device and get that to talk with the rest of the car, or to use the encoder already mounted on the drive shaft. Both had their disadvantages, with the encoder reading having the tendency to drift and the inaccuracy of the path chosen on the track and the GPS with its CEP of ±2.5m. When the RCP2 was bought it came with an GPS solution already implemented, this made the choice of having both of them easier, more can be found in Section 3.4. The next problem arouse was to filter the readings of both the GPS and the encoder to have a reliable positioning source. Due to priorities and limited amounts of time, the filtering is currently not implemented.

3.3 Constraints

The optimization is limited by the constraints of the physical system, meaning that the controller is not able to operate outside the limits of the system. These limits are,

$$U_{cap} \in [39, 48] \text{ V} \tag{3.1}$$

$$\nu \in [0, 15] \text{ m/s} \tag{3.2}$$

$$a_{\max} \in [-1, 1] \text{ m/s}^2 \tag{3.3}$$

where U_{cap} is the voltage level of the super-capacitor, ν is the speed and a is the acceleration in every time step. Due to the fact that there is a lower limit to the voltage level of the super-capacitor, it is necessary to change drive mode to engage the ICE in order to regenerate and store energy until the upper limit is reached. Since the optimization is currently only done in the top layer, there is a need for the voltage limit to be considered manually in the model.

3.4 Position recognition

The optimization bases the output reference speed on the current position on the track. This yields the need for a position recognition with an accuracy precise enough to be able filter it with sufficient results. The track itself, rather then time is discretized in order to get a more accurate position in relation to the tracks topography.
There are two ways of finding Elba's position on the track. The first way is a dead reckoning system based on the shaft encoder [12, p. 49], which calculates the position based on the amount of rotations of the shaft. The second way is based on the GPS system implemented in the race capture pro 2, where the GPS signal is taken from it's raw form and reshaped with a Lua-script[1] into a CAN-message that is sent on the CAN-bus.

3.5 Simulink implementation

The complete description of the algorithm is found in [8] and the implementation is based on this thesis. The position calculated from the encoder readings should be filtered in a Particle Filter block together with GPS readings. However, the Particle Filter itself is not implemented at the moment and is considered to be something future groups need to work on. These two positioning systems is supposed to be used to get the estimation of the distance Elba have travelled on the track.

There are three inputs into the three dimensional optimization lookup-table, total time elapsed since the race started, speed of Elba and distance travelled by Elba.The output of the block is an acceleration reference which needs to be converted to an reference speed since Elba is currently controlled with speed request.

3.6 Simulation

A race can be simulated with the plant model described in 2.3.1 and [12]. This was done for the case with a static reference speed and the optimal speed as calculated by [8].

[1]Lua is a dynamically typed scripting language, www.lua.org

3.6.1 Static reference speed

One lap around the track was simulated using the plant model with a constant reference speed of 7 m/s (the slowest allowed speed to be able to complete the race in time).

The fuel consumption in km/l fuel, f_c was calculated according to

$$f_{tot} = \frac{d_l}{f_i + f_c}, \tag{3.4}$$

where d_l is the distance of one lap, f_i the fuel consumed by the ICE and f_c the equivalent amount of fuel that the super capacitor has been discharged by since the start of the race, calculated as

$$f_c = \frac{({u_{c_0}}^2 - {u_{c_{end}}}^2)c_c}{2k}, \tag{3.5}$$

where u_{c_0} is the initial capacitor voltage, $u_{c_{end}}$ is the capacitor voltage at the end of the race, c_c is the capacitance in the capacitor and k is the conversion ratio from litre ethanol to energy in joule, retrieved from [16].

This resulted in $f_{tot} = 172.8\ km/l$.

3.6.2 Optimized reference speed

Using the optimized speed controller as a lookup table (produced by [8]) dependant on vehicle speed, distance and elapsed time, a new simulation could be produced. The resulting speed and vehicle height position can be seen in Figure 3.1

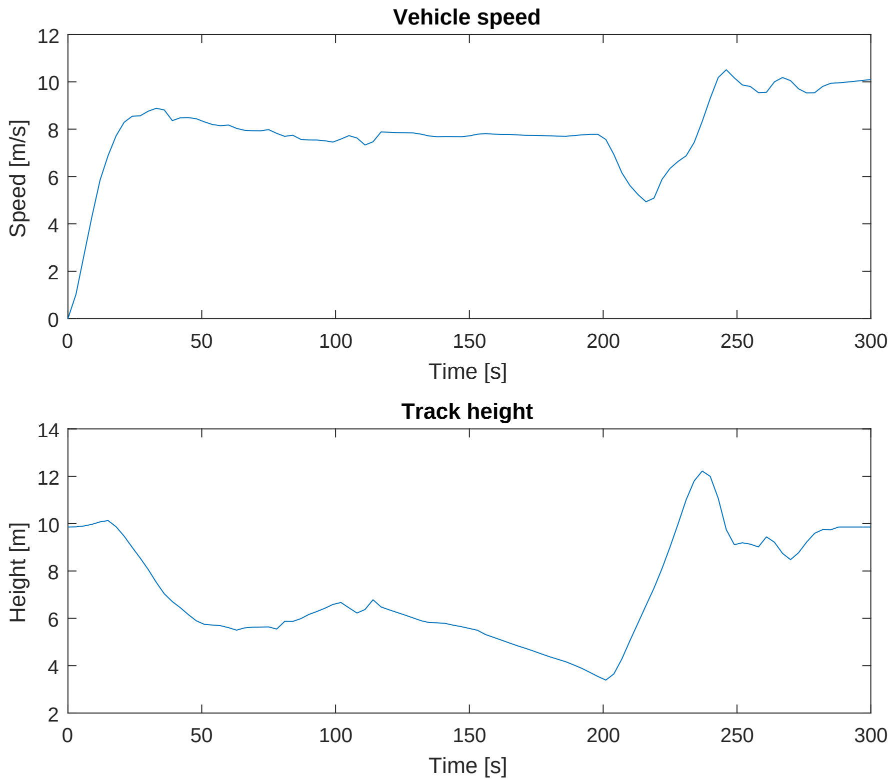


Figure 3.1: Plots of vehicle height and speed as a function of time.

The amount of kilometers travelled per liter fuel f_{tot} was calculated according to equation 3.4. This resulted in $f_{tot} = 194.1\ km/l$.

4 | Testrig

4.1 Introduction

When designing a complex system such as a hybrid vehicle, continuously being able to test the system is important in order to validate that the requirements are met and to verify the models. To be able to do a full system test, the car has to be physically run on a track. This can be cumbersome, or in the case of the London track, impossible at times. Therefore, there was a decision to design and build a testrig. During the design process have the V-model approach been used with a set of live requirements and continuous unit and integration testing. The overall goal is to not only be able to do a faithful simulation of the EcoCar track in London, but to be able to simulate any track (with certain limitations on power and speed demands) to the test rig and simulations on the car.

4.2 Requirements

The requirements on the test rig are designed to capture the essential demands on the system. Firstly, the high level user requirements are set. These are set to capture the problem and to describe the goal of designing the system [7]. The User requirements are then used to develop the System requirements that describes the limitations and demands on the system and its subsystems.

4.3 Design decisions

When designing the testrig, there were a number of issues, each with multiple solutions. The ones with the most impact and highest importance are explained in this section.

4.3.1 Concept design

There were two basic concepts that were discussed, the first concept was to connect the testrig to the car by removing the wheel and bult it on to the drive shaft of Elba. The second concept was to construct some sort of rollers that Elbas driving wheel would be placed on and apply a torque via a DC motor to the rollers. The second concept was chosen and the work continued with the roller concept. Reasons for this are explained further in Section 5.3.4.

4.3.2 Regeneration

Another problem that needed a solution was the handling of regenerated current. As seen in Figure 4.4 the forces produced by the testrig will at almost all points of the track need to be opposite to that of Elbas rolling direction. This means that the DC motor will work as a generator most of the time, since the torque from Elba and the Testrig be in opposite directions. Many different ideas of ways to solve this problem of how to dissipate the energy, all with the fundamental idea to use power resistors in order to transfer the excess energy into heat were discussed. Both where a manual switch could be used to lead the transfer the energy when needed. The final solution included a super capacitor to store energy temporarily to be used when simulating a downhill, and a way of automatically burning excess when the super capacitor was fully charged. The complete setup is explained with greater detail in Section 4.4.

4.3.3 Control

The desired output of the testrig is the combined external forces that affect the car at any given time on a track. This means that the output to control is the torque on the rollers. The team chose between two ways of doing this. The first was to measure the torque directly using an appropriate sensor. The second idea was to measure the current applied to the motor and calculate the torque from the current. The team decided to use current control. Further explanation as to why this was chosen can be seen in Section 5.3.5.

4.4 Hardware

The testrig is composed of two rollers mounted on a metal frame together with a DC motor and an encoder to keep track of the speed of the motor.

The motor is connected to the rollers by sprockets and chain with a gearing ratio of two. A model of the system can be seen in Figure 4.1.

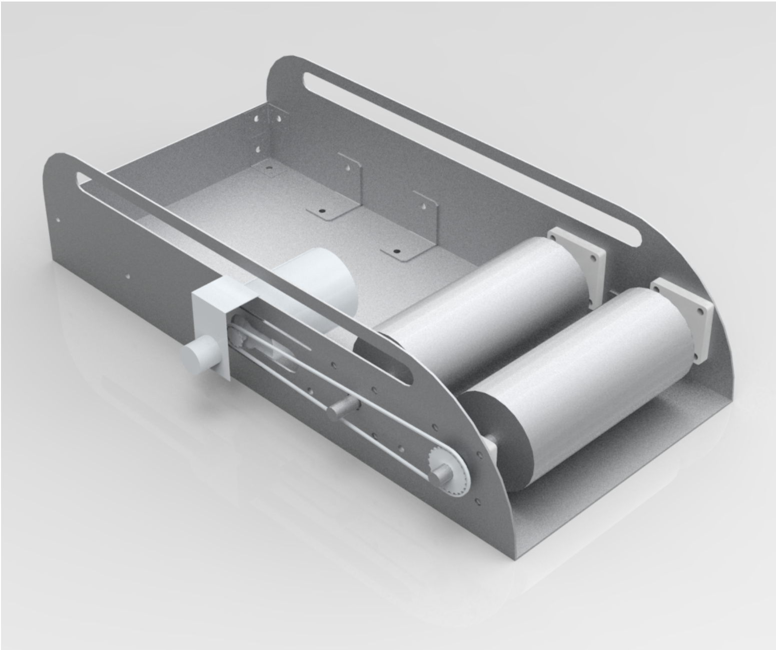


Figure 4.1: CAD model of the testrig without the chain guard for increased visibility.

«««< HEAD To control the DC motor an Arduino Mega 2560 microcontroller calculates the current that should be applied to the motor (explained further in Section 4.5 and Section 4.6), this reference signal is used by the ESCON driver to control the current in a local feedback loop.

The current generated by the DC motor is stored in a supercapacitor, connected in parallel with motor driver. The microcontroller monitors this voltage via a voltage divider since the input voltage to an Arduino Mega 2560 can be max 5V. If more energy is generated than the supercapacitor can handle, the microcontroller will close a relay and the current will go between six parallel power resistors and ground, and it will remain closed until the supercapacitor has discharged to a lower limit. Then will the microcontroller open the relay and make the supercapacitor able to recharge again.

A problem that exists with the Arduino microcontroller is that it is exposed to disturbances from the motors and ICE. These disturbances have at times made the microcontroller crash and restart, which of course affects its abilities to control the energy dissipation from the supercapacitor. To ensure that the supercapacitor does not exceed the maximum rated voltage of 48 volt the voltage is monitored by a person with an externally applied voltmeter. If the voltage rises above 48 volt due to a crashed microcontroller an emergency stop button is pressed which inhibits the testrig motor driver from generating energy.

The upper level of the voltage in the supercapacitor, where the microcontroller should close the relay, was decided by the specifications of supercapacitor to be no more than 48V. To have some margin of error the upper limit was set to 47 V. The lower limit of the voltage should not be too low since the motor will have different dynamics depending on voltage applied. Also it shouldn't be too close to the upper limit in order to avoid the relay to constantly be turned on and off. It was decided to set the lower limit to 45V. The system is connected to a 45V voltage supply via a rectifier to avoid generated current to flow into the power supply. A basic schematic of the setup can be seen in Figure 4.2.

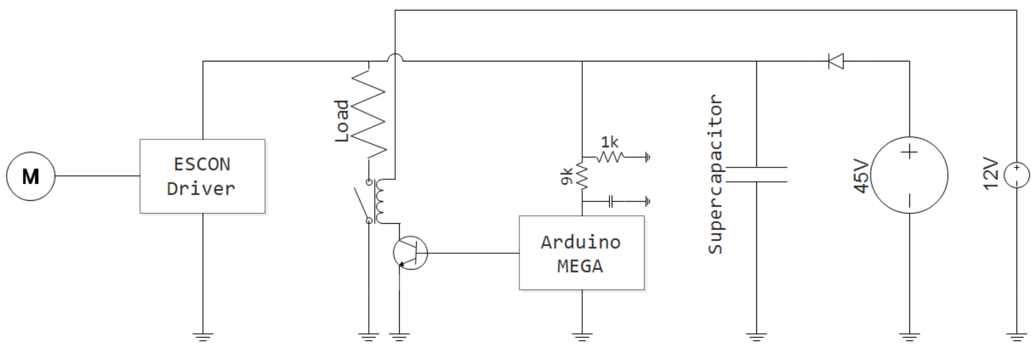


Figure 4.2: Schematic of testrig wiring to control the voltage supplied to the driver.

4.5 Car dynamics

The calculations in this section are in many ways the same as the calculations given in the previous teams report in [12]. Though some of the equations are repetition of what was done last year, they are done here again with some improvements and more references to make the derivations of the equations clearer.

When simulating a track, one needs to know the force exerted by the environment on the car. A graphical representation of the forces that act on the car is given in Figure 4.3.

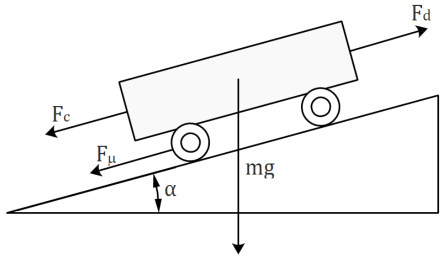


Figure 4.3: Dynamic model of Elba.

The motion equations on the system are

$$m\ddot{x} = F_d - mg\sin\alpha - F_c - F_\mu, \tag{4.1}$$

where F_d is the effective driving force of the car, m is the mass of the car and $alpha$ is the slope from the horizontal plane. The resistance terms F_c and F_μ are air and road resistance, respectively. The air drag D around an object can be calculated as [11]

$$D = C_D A \frac{\rho v^2}{2} \tag{4.2}$$

with object velocity v, surface area vertical to the movement direction A and air density ρ. Most terms in Equation (4.1) are constant throughout a driving instance. Rewriting to

$$C_{tot} = \frac{C_D A \rho}{2} \tag{4.3}$$

yields a simplified equation that only depends on the velocity,

$$F_D = C_{tot} v^2. \tag{4.4}$$

The total drag coefficient C_{tot} will depend on the vertical area, the density of air and the drag coefficient C_D. The air density is considered to be constant and is known. The area of Elba can be estimated using simple methods. Finally, the air drag coefficient C_D is unique to each and every object and is determined experimentally. For this project, the estimations given for a passenger car is used. Detailed calculations and values are given in Appendix A.

The rolling friction of a car is modeled as a step function, being non-zero at all velocities that are not zero.

With the air drag, rolling friction and gravity terms known, only two terms of Equation (4.1) are unknown. To fully model the cars dynamics, the inertia term needs to be modeled. Since the weight of the vehicle is known, $\ddot{x}$ needs to be derived for an accurate system model. Knowing the radius of the rollers and the cars wheels, the linear acceleration can be calculated by measuring the rotational acceleration on the roller. This is done by an incremental encoder on the roller shaft. Rotational speed is calculated in the microcontroller and rotational acceleration is derived from rotational speed. Using the roller radius, r_r, the linear acceleration is calculated.

Rewriting Equation 4.1 and 4.4 and the friction force gives the desired linear testrig simulation force on the right hand side,

$$F_{tr} = m\ddot{x} + mg\sin\alpha + C_{tot}\dot{x}^2 + F_{\mu}. \tag{4.5}$$

Using the height profile of the London track and the plant model of Elba, F_{tr} during an entire lap could be simulated, as shown in Figure (4.4).

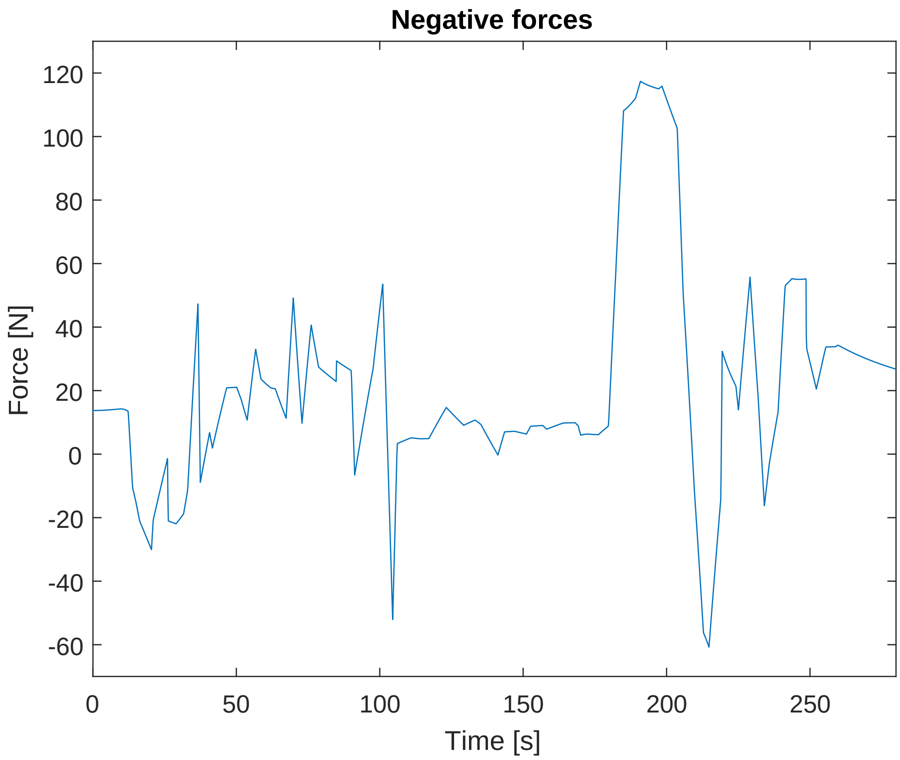


Figure 4.4: Negative forces acting upon Elba in one lap.

4.6 Testrig dynamics

In order to let the testrig output the correct linear force to the car, the controller for the testrig need to know the dynamics of the testrig itself. This is to compensate for internal frictions and inertias. The driveline of the testrig has two separate steps, the motor and the roller, connected by a chain gear with gear ratio n_{chain}. A principle schematic of the testrig from motor to roller is displayed in Figure 4.5.

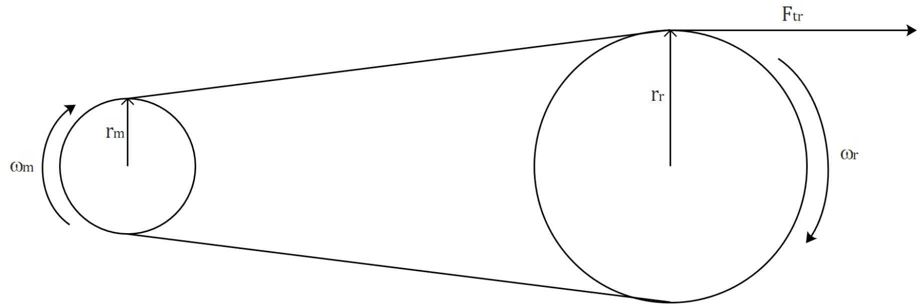


Figure 4.5: Principle schematic of the testrig from motor to roller.

The dynamic equations for the rollers are

$$J_r \dot{\omega}_r = F_{tr} r_r - d_r \omega_r - \mu_r, \tag{4.6}$$

where J_r is the inertia of the rollers and ω_r is the rotational velocity of the roller. The frictional terms are the viscous friction d_r and the constant friction μ_r which is modelled by the Karnop model.

Connecting the rollers and the motor is a chain gear. It is modelled as a generic gear box. The gearbox model has no internal friction. There is always friction in a chain gear but it is expected that this friction will be incorporated in the total system model and the friction free representation is deemed adequate. Using Equation 4.6 and (motor model) along with the gearbox model, the total testrig dynamic model becomes

$$T_m = \frac{F_{tr} r_r + J_{tot} \dot{\omega}_m + d_{tot} \omega_m + \mu_{tot}}{n}, \tag{4.7}$$

with motor torque T_m, simulation force F_{tr} and motor rotational velocity ω_m. The inertia term is the combined inertia of the motor and roller,

$$J_{tot} = J_m + J_r \frac{1}{n^2}. \tag{4.8}$$

The friction terms are combined terms as well, namely

$$d_{tot} = d_m + d_r \frac{1}{n} \tag{4.9}$$

and

$$\mu_{tot} = \mu_m + \mu_r. \tag{4.10}$$

The power P_m required for the motor on the testrig was calculated as

$$P_m = T_m \omega_m \tag{4.11}$$

Using the London track and the plant model of Elba, P_m during one lap could be simulated, as shown in (4.6).

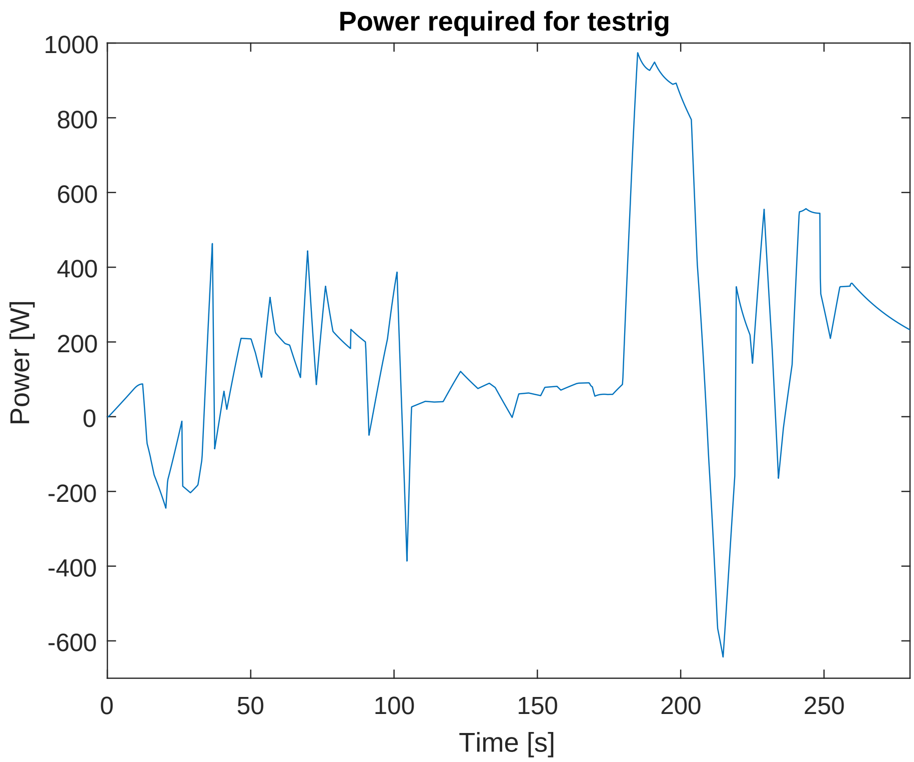


Figure 4.6: Power required for the motor on the testrig.

Figure (4.6) shows that the maximum required power from the testrig motor is 1 kW.

4.7 Identification

Having obtained the dynamic equations of the system in Equation (4.7), a system identification is done to determine the parameters of the system. The parameters are then used in the open loop current/torque controller. The controller is run in open loop for the torque, i.e. there is no direct torque feedback. To get the desired torque output, the current is controlled via a closed loop feedback controller and torque is calculated from the actual current. With a knowledge about motor parameters and the dynamics of the system, the actual torque can be estimated.

4.7.1 Motor parameters

To acquire the motor parameters calculations had to be made, since it did not exist any datasheet to the DC motor in use. The motor parameters needed was the internal resistance, R_a, and the motor constant, k_ϕ. The motor was run at idle for two different voltage levels and the current and the speed in terms of revolutions per minute (RPM) where noted for those specific voltage levels. The speed in angle velocity was calculated from RPM, and together with the current for two different instances of voltage level, R_a and k_ϕ was calculated. The equation

$$U = R_a I + k_\phi \omega \tag{4.12}$$

found in [5] was used in an equation system to derive the internal resistance and motor constant.

4.7.2 Hardware setup

The testing is processed in Matlab and Simulink. Input data is gathered from the real system and is then fed into the model afterwards for model comparison. This has the advantage of doing a physical test once, recording the data and the be able to test it on the model without setting up the test system again. Output data from the testrig, rotational velocity of the motor, is also collected and used as a reference for the model.

To measure motor voltage, a computer oscilloscope was used (Digilent Analog Discovery 2). The oscilloscope has an open C API, allowing its interface to be customized. An S-Function block was made that allowed the oscilloscopes measurements to be directly recorded in Simulink. To make sure that the model ran in real-time in Simulinks normal mode, a Real-time constraint block was added to the simulink model. The probes of the oscilloscope were attached to the positive and negative pole of the motor. All data was recorded into a Simulink Datastruct that could then be used as input for the model.

For recording the output data, rotational velocity, an incremental quadrature encoder was used. The encoder pulse data was recorded and converted into velocity by the test rig ECU. The Simulink model for the ECU was run on external mode and encoder data was saved.

Because of software limitations, the oscilloscope and the testrig ECU can not be run in the same Simulink instance. This means that two separate models are run simultaneously, one recording the input and one recording the output.

4.7.3 Identification process

The testrig is a rather simple system in principle. It consists of an electric motor attached to a load with inertia and friction, see Figure 4.7. This is consistent with most standard models of an electric motor (see for example [4], [10] and [9]) and the systems dynamics are therefore assumed to be well known mathematically. When the mathematical model of a dynamic system is known, a parametrized model based on the real physical parameters of the system can be used in the identification process. This is known as a Gray-box model [9]. This approach is beneficial because the unknown parameters are based upon real physical parameters and are thus easier to estimate and relate to the model.

The goal of the system identification is to estimate the unknown parameters of the system well enough so that the testrig can be current controlled based on a desired net output torque. This requires knowledge about friction losses that occur between the torque source and the torque output. Model accuracy is therefore important but must be weighed against needed processing power in the microprocessor used to control the rig. A higher-order model will require more processing power to be solved online and might negatively affect the real-time performance of the system. To find a balance between accuracy and processing power, an iterative identification process is used, described in Figure 14.1 in [9]. Firstly, accuracy and performance requirements are set to create an evaluation frame for the identification. These are used for the evaluation of the model. The last loop in the diagram is repeated with progressively more complex models where parameters are added or the order is increased. This is done until the model is accepted.

The requirements are set to match accuracy demands for the testrig. Model fitting is done against step responses of different amplitudes. The size of the amplitudes are set to capture as much of the dynamics of the system as possible but are limited by the hardware. At higher voltages (i.e. rotational speeds), disturbances from the motor causes interruption in the communication between the PC and the testrig ECU and data can then not be captured. The upper step amplitude is set to the maximum value that gives reliable data capture.

Model validation is then done by comparing the behaviour at sine wave inputs of the simulated system with the real systems output. This requirement is set loosely with regard to absolute accuracy because of the difficulty to measure the exact voltage output to the motor since the driver outputs a PWM signal with varying polarity and duty cycle depending on the demanded voltage. This validation is done to ensure that the system captures all the essential dynamics of the real system. The exact requirements set on the model can be viewed in their entirety in Appendix D. but briefly, the model shall have a max 5% error in rise time and steady state value with the real system for step inputs of ± 5, ± 10 and ± 20 volts. The model shall also capture the dynamics of a sine wave input of amplitude ± 2, ± 8 and ± 16 volts.

4.7.4 Gray-box model

A general mathematical model for the testrig is produced. This model is then used as a reference for simplified models used in the identification process. To get the complete system model, the dynamic model from Equation (4.7) is combined with that of a DC motor. A principle schematic of a DC motor is given in Figure 4.7. V_A is the voltage input, R_A and L_A are the internal resistance and inductance respectively, i_a is the motor current and V_C is the back-emf. J is the inertia of the motor and ω_a is the rotational velocity.

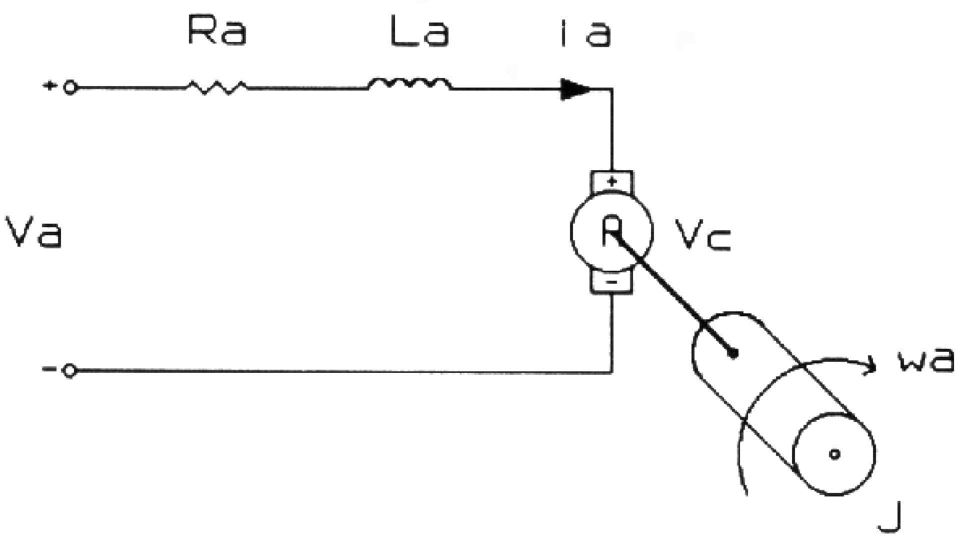


Figure 4.7: DC motor schematic diagram.

Using Kirchhoffs loop rule along with

$$V_C = k_\phi \omega \tag{4.13}$$

and

$$T = k_\phi \omega \tag{4.14}$$

gives the electric dynamics of the motor,

$$\begin{cases} V_A = R_A i_a + L_A \frac{di_a}{dt} + k_\phi \omega \\ J\frac{d\omega}{dt} = k_\phi i_a - d\omega - \mu. \end{cases} \tag{4.15}$$

Performing a Laplace transform and rewriting Equation (4.15) one gets a second order model for the motor as a transfer function between voltage and rotational velocity,

$$\omega = \frac{k_\phi}{(sJ + d)(R_A + sL_A) + k_\phi^2} U_A - \frac{sL_A + R_A}{(sJ + d)(R_A + sL_A) + k_\phi^2} \mu. \tag{4.16}$$

Model 1

As a first attempt, the model in Equation (4.16) is simplified by making the following assumptions:

1. Inductance is small enough to be negligible.
2. Static friction is small enough to be negligible.

With these assumptions Equation (4.16) becomes a first order system,

$$\omega = \frac{k_\phi}{sJ + dR_A + k_\phi^2} U_A. \tag{4.17}$$

Equation (4.17) can be rearranged to a standard first order transfer function form, yielding

$$\omega = \frac{K}{sT + 1} \tag{4.18}$$

where $K = k(1 + \frac{1}{Rd})$ and $T = \frac{J}{\frac{k^2}{R} + d}$. Using the final value theorem, setting $s = 0$, K can be seen to be the steady state gain of the system and T is the time constant [10]. Seeing how K only depends on one unknown variable, d, the model is fit to a steady state gain first using the viscous friction variable. The inertia J is then fitted using the time constant of the response and d as a known variable. The step response with the largest amplitude is used for fitting the data. This is where the effects of the viscous friction are the largest and it should give the highest fidelity model available.

Evaluating the results, it can be seen that the model fits the real system very well around the set point of 20 V. Figure 4.8 shows the step response at 20 V. The deviating value in the rise of the is an error induced by the revolutional velocity capturing algorithm in the microcontroller.

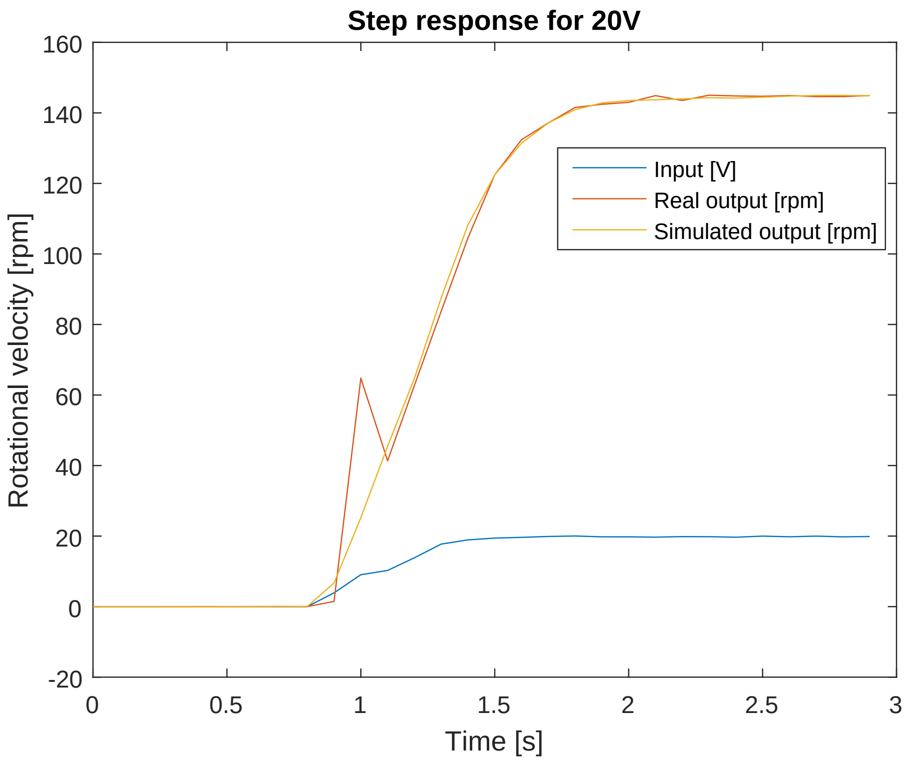


Figure 4.8: Step response for a 1st order model at 20 V.

However, the static error increases the further away from the setpoint the tests are run, see for example Figure 4.9.

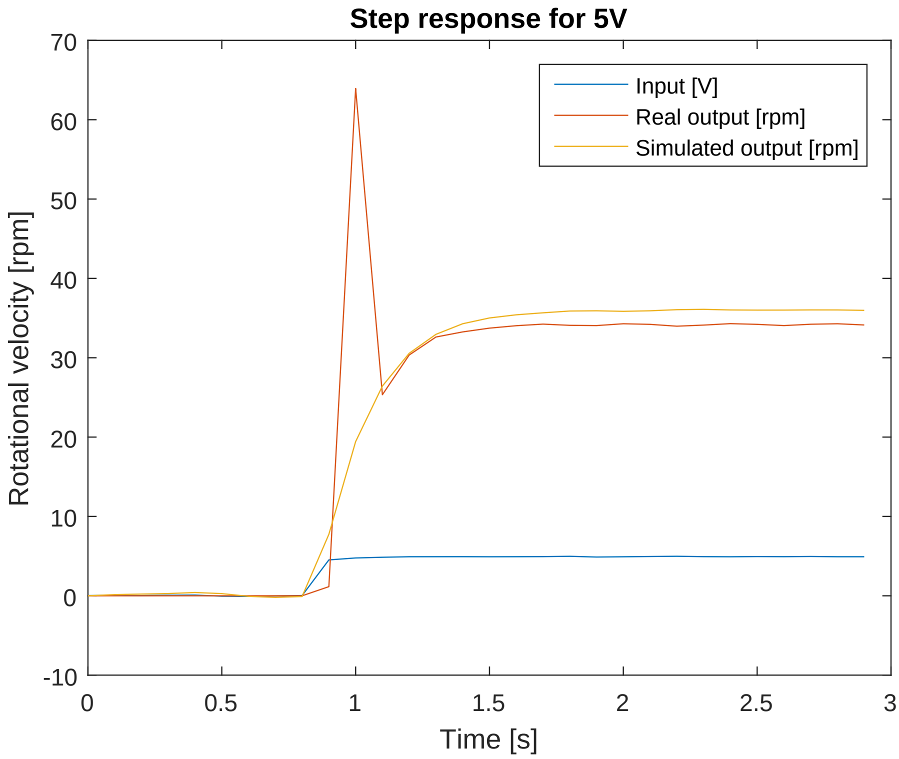
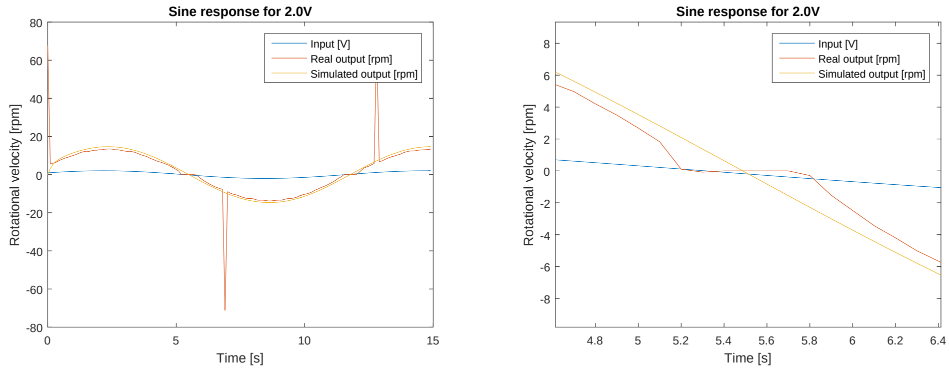


Figure 4.9: Step response for a 1st order model at 5 V. Note the steady state error compared to the set point.

Also, when validating the model using a sine wave at low amplitude, there is a significant discrepancy in the model performance compared to the real system at the turning points. The real system needs to reach a certain voltage before it can overcome the initial friction whereas the simplified model does not. In



(a) Full response. (b) Magnification on turning point.

Figure 4.10: Sine response for first order model with no inductance or static friction.

The full set of step and sine responses for this model are given in Appendix B.

Model 2

The previous model showed good correspondence for the time constant but had a steady state error when not at the set point. It also did not catch the dynamics at the turning of the rig. There is a missing dynamic that is not captured with the simple model. The fact that there is a threshold needed for the testrig to start turning hints that a static friction is present in the system and that it is significant enough to directly affect the dynamics in a noticeable way. Therefore, the model fitting is reiterated with a model that takes the static friction into account and only makes the assumption that the effect of the motor inductance is negligible. The new model achieved is then

$$\omega = \frac{k_\phi}{sJ + dR_A + k_\phi^2} U_A - \frac{R_A}{sJ + dR_A + k_\phi^2} \mu. \tag{4.19}$$

A static friction is a disturbance torque that at its simplest has a constant amplitude and changes with the direction of velocity. This representation is not suitable for numerical solving because of the discontinuity that occurs when the system turns. To counter this, a stick-slip region is added around the origin, i.e. the turning point. Within this stick-slip region, the friction force is equal to the internally applied torque from the motor until the static friction maximum value is reached. After that, the friction torque is constant. This friction model is called the Karnop friction model, see Figure 4.11.

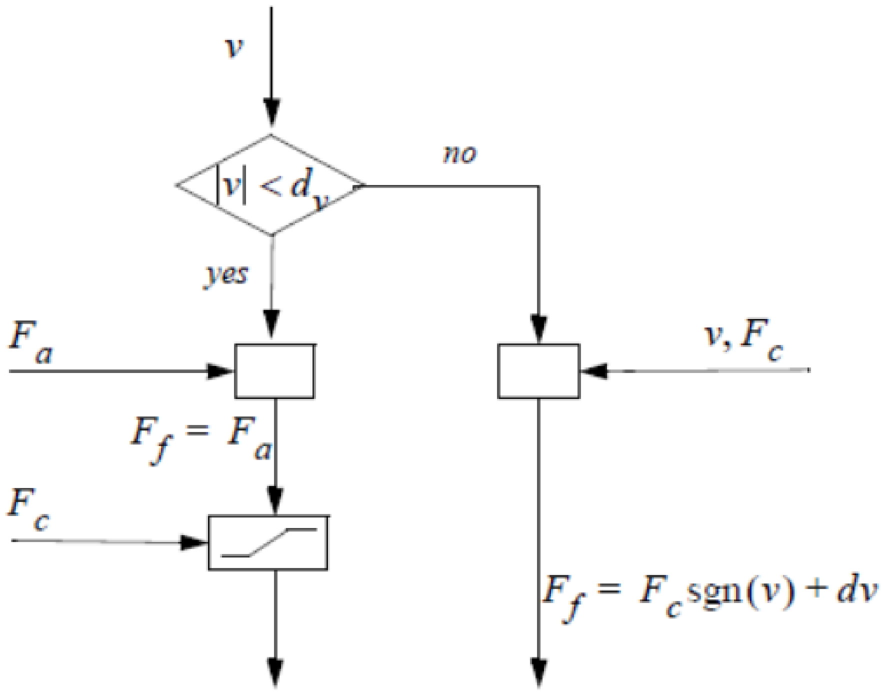
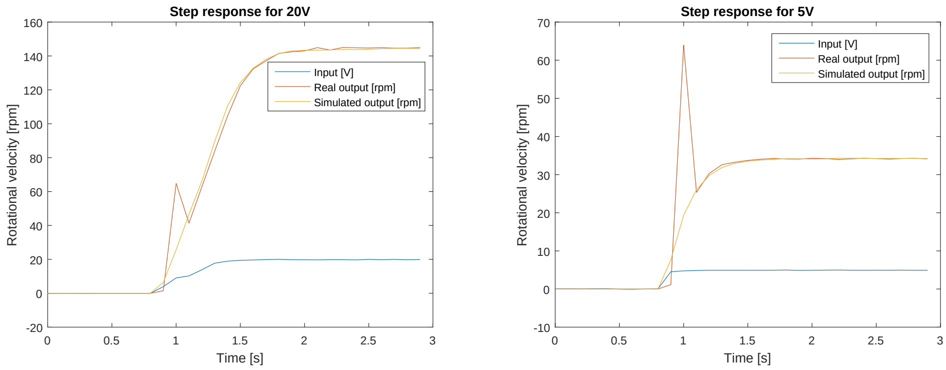


Figure 4.11: Schematic of Karnop logic. v is velocity, F_C is Karnop friction, F_a is applied force, d_v is velocity threshold and F_f is friction force. Image from lecture series in MF2007 Dynamics and motion control at KTH, courtesy of Dr Lei Feng.

Karnop allows numerical solvers to be used on the model but it also introduces 2 new parameters to fit. These are the static Coulomb friction F_C and the velocity threshold d_v.

To successfully fit the parameters of the model, a systematic approach based on the physical effects of the parameters is used. The viscous friction and inertia is firstly estimated at the largest input step. At this point, viscous friction should be dominant over the static friction, allowing a good estimate of these parameters with as little disturbance as possible. After a good model is found, the two static friction parameters are fitted by trial and error. Lastly, the model is fitted to the largest step again, fine tuning the inertia and viscous friction parameters.

The model now follows the real response of the system at all three step sizes, with a very small steady state error. Step response for the edge cases are shown in Figure 4.12a and 4.12b.



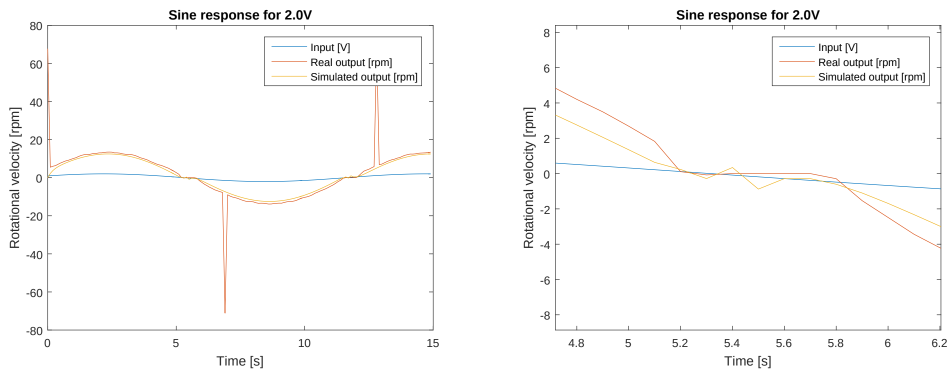
(a) 20 V step input.

(b) 5 V step input.

Figure 4.12: Step responses for the edge case of the first order system with Karnop friction.

The steady state error has a maximum error of 1.5% over all three input step sizes and the rise time has a maximum deviation of 4.1%. There is an area at low speeds in which the model and the real system do not correlate well but the real system and the model converge at the end of the step inputs.

In the validation step, the model follows the behaviour of the real system well. In Figure 4.13a and 4.13b, it can be seen that the model follows the real system well in the turning point. However, there is a static following error but this was not part of the requirements. The model is therefore accepted as suitable. The full set of step and sine responses are given in Appendix B



(a) Full response.

(b) Magnification on turning point.

Figure 4.13: Sine response for first order model with static Karnop friction and no inductance.

4.7.5 Result analysis

In summary, a first order model in which the effects of the inductance are ignored is used. Friction is modeled using the Karnop model with a stick-slip area at low rotational velocities and a viscous friction outside the stick-slip zone. The inertia of the model J is 0.0135kgs^2 and the viscous friction d is 0.078N m rad^{-1} s. The stick-slip threshold d_v is 0.01rad s^{-1} and the static Coulomb friction F_C is 0.02N m. The value of the inertia is considered to be feasible. There are no exact measurements available for the internal diameter of the roller but an estimation made in Solid Edge gives a moment of inertia of 0.022kilogramm^2. Being a rough estimation, it gives an indication on that the inertia estimation is correct. The estimated value of d is rather high, considering that there will be roughly 1 Nm of viscous friction torque for every 12 rad/s of motor speed. This can be expected of the system. Misalignments and the chain-drive most likely adds a significant amount of viscous friction. Static torque is comparatively small compared to other losses in the system which might be because of the magnitude of the viscous friction. The static friction does however have an important effect on the system and cannot be ignored. The model fulfils the requirements and is considered to be good enough to use in the final system.

5 | Discussion

The purpose of this section is to give the authors thoughts and considerations on how the different design decisions and project as a whole have turned out with the benefit of hindsight. Not everything has been clear from the beginning and a lot of lessons have been learned along the way. The easiest way to communicate this is to start with the project as a whole and then move into the different parts of the project one by one.

5.1 Elba

5.1.1 Clutch decisions

Figure 2.4 shows how the capacitor voltage behaves in the different drive modes. The time that the clutch moves when engaging and disengaging is around 7 seconds which is very long. This was decided because then an endpoint is always reached when disengaging, and it is possible to know exactly how long is necessary for a good connection when engaging the clutch. It is clear in this figure that this process consumes a substantial amount of energy, and should preferably be kept as short as possible. To improve the performance, one way could be to implement a current sensor and then know that when the current rises to a certain value, then clutch plate is firmly stuck to the drive shaft and no more current is needed.

5.1.2 ICE and controlling it

Getting the new engine to work in the the car took the most time compared to what we estimated. Starting on ethanol has proven to be a challenge and we later learned that we had to choke a lot. But getting rid of the bevel gear was a major improvement and although there are vibrations when running nothing mechanical broke due to the uneven torque applied from the engine.

After the competition we added the ability to control on the lambda value which also improved the overall operation of the engine, and made it easier to get running. Still there is a risk of making the spark plugs wet when choking.

The power output of the new ICE is larger than previous years (even though the cylinder volume is smaller) and this goes against what the previous team recommended us to do. Our motivation is that this is not as big of a problem if the ICE is used in the hill of the track. There the BLDC can both apply positive or negative torque in the hill which has larger demand on torque from the car than a flat track.

5.2 Optimization

The optimization was one of the things we really wanted to focus on when the project started. The group really thought that the optimization problem was of real importance due to the new track in London. Even so to the extent that the state of the art report that the group wrote during the spring semester was dedicated to the optimization problem. Once the report was finished there was a lot to work to do on Elba in order to get the car ready for London. This in combination with the fact that the thesis project was not ready with the lookup table until a couple of days before the race made the work with the optimization stagnate. There was simply no time to implement the optimization before it was time to leave for London. Once we got back from the summer brake the main focus was on correcting the errors that were found during the race and to get Elba fully functional. There was also an addition to the workload when the project of building the Testrig started. There was however work done with getting the positioning system to work, when the RCP2 arrived the was a lot of work was put into getting the GPS signal to be sent over CAN. Once this was accomplished the implementation structure was also developed and the structure of the system is completed with all the signals and blocks in the right place. The blocks themselves are only working to some degree and retrieving the GPS signal from the CAN and transferring this to Simulink is not yet completed. The particle filter will also need to be developed were both the encoder and GPS can contribute to getting the correct distance travelled on the track. We still believe that the optimization is of great importance and that a working implementation will improve the performance in the race. This is also what the simulations is showing when comparing the results from Section 3.6.2 to the results in Section 3.6.2.

5.3 Testrig

5.3.1 Requirements

Having good requirements gives a common goal for everyone to work towards. At the start of the project, not much thought was given to setting requirements first and then work towards fulfilling them. They where instead treated as implicit to the problems to be solved and an estimation of what was acceptable end goals were made up as we went along in the project. The lack of real requirements led to difficulties when the projects from the other subgroups where incorporated into the final design of the car. For example, the clutch improvements that were made by the machine design team did not meet the expectations of the mechatronics team i.e. our implicit requirements were not the same. Had a predefined set of requirements been set up beforehand, the consolidation and evaluation of the design would have been easier.

To make result evaluation easier, and to get a clearer definition of done, requirements where set before work on the testrig started. There were some difficulties with this since we were customer and the supplier, i.e. user and developer. To get a clear distinction between the roles, it was decided that as many user requirements as possible would be set with the SEM rules as a base. Looking back, this was a good decision. We have been able to source many clear high-level requirements from the rules, for example the requirement that the testrig should be able to simulate the full London track. We could then sit down as a design team and reduce the abstract user requirements to technical system requirements. This separation of roles has helped us set fair requirements that set demands on the system design but still allows us to create feasible definitions of done.

5.3.2 Requirements Engineering system

When evaluating which software to use to store the requirements, we made special requirements for how this software should work. It was important to have traceability, both between requirements and to who has made changes, and that the system was easy to use. Emphasis was on an easy learning curve. Everyone in the team has used IBM Rational Doors for requirements engineering in a previous course, but we all found it cumbersome to use and too packed with features for what we needed. Since only a core set of features was needed, an alternative path was taken. Having only the essential features and being able to add new ones as they are needed has been valuable for the team. Even though not everyone in the team has experience with

HTML programming, the use of Markdown along with a standard template for requirements still allow everyone to write new and edit requirements.

5.3.3 Clutch decisions

Figure 2.4 shows how the capacitor voltage behaves in the different drive modes. The time that the clutch moves when engaging and disengaging is around 7 seconds which is very long. This was decided because then an endpoint is always reached when disengaging, and it is possible to know exactly how long is necessary for a good connection when engaging the clutch. It is clear in this figure that this process consumes a substantial amount of energy, and should preferably be kept as short as possible. To improve the performance, one way could be to implement a current sensor and then know that when the current rises to a certain value, then clutch plate is firmly stuck to the drive shaft.

5.3.4 Testrig concept design

As described in 4.3.1 it was chosen to use rollers for the testrig instead of attaching a motor directly to the driving wheel. This design had a number of benefits. Firstly it is easy to shift between testing the car on the testrig and on a real track. This is an important feature, especially during the competition. Secondly it can be used on other cars, for example Sleipner. It is however more difficult to control since it is not guaranteed that there is no slip between the wheel of the car and the roller. This property can be modeled better in the future and overall the team feels that the current concept design for the testrig has the highest potential in the long run.

5.3.5 Testrig control

As described in 4.3.3 the variable monitored to control the torque is current applied to the motor. This choice was made because of time and hardware constraints. In theory, since the motor torque constant of a DC motor is constant, the torque can be calculated by measuring the current fed to the motor if losses in the system are known. In practice, it is difficult to predict losses accurately and the convoluted way of calculating the torque adds another layer of possible errors. It also puts rather high demands on how well the system is modelled; the torque estimation can never be better than the accuracy of the model. An optimal solution would of course be to fit a torque sensor to the testrig and run the system on a closed loop with current as the control variable and torque as the output. However, under the circumstances, the group considers the open loop current control approach to be the best choice. Even with a lower output accuracy, it still gives a good proof of concept of the testrig and shows that a rolling highway simulation on Elba can be done successfully. For future improvement of the testrig, torque control should be considered. It is however not deemed to be of the highest priority.

5.3.6 Testrig identification

As discussed in the previous section, the current control approach is not optimal and it should be considered to use another final design for the control of the testrig. Therefore, it has been important to set accuracy requirements that are "good enough". A model with a good accuracy is needed for the operation of the current setup. This allows the concept to be proven and also lets next years team use the testrig as a tool for getting preliminary data at the start of the project. However, spending too much time on refining the model would be counterproductive since future versions of the system will not be as dependent on a high accuracy model. Therefore, the iterative approach used has been a good way of finding the right balance between accuracy and time spent. The chosen model has obvious flaws. Because of the hardware setup, reliable data for the sine wave input could not be collected and had to be roughly estimated from the settings used in the DC motor driver. This means that the sine wave input could not be used for more than a way of validating model behaviour instead of taking exact measurements. It is difficult to know whether the steady state error for the sine wave input is because of the model or the estimation of the voltage. It was good however to see that the model performed well in the area where the testrig started moving from a stand still.

One large caveat of the parameter estimation is that it did not take measurement noise into consideration. A big improvement on the reliability of the data could be achieved by using the statistical methods in [9]. Usually, measurement noise is modelled as white noise through a suitable filter. The iterative process used in the parameter estimation could be continued to include measurement noise. This is something that could be incorporated into further iterations of the model identification process used, along with taking the inductance of the motor into account. Having a flexible process with clear gates between each model iteration has been very beneficial for the group and has allowed us to make judgements on how much time to put on improving the models accuracy.

Little consideration has been taken to quantization errors. The encoder has a high resolution, 1024 pulses per revolution, which is assumed to be high enough so that it has a small impact on the fidelity of the results. Also, the sampling rate was set to 10 Hz. This was the highest that could be used by Simulinks external mode to get reliable communication with the microcontroller. It does follow the rule of thumb that the sampling rate should be 10–30 times faster than the fastest dynamics in the system and the sampled input and output was exact enough so that most dynamics where rather smooth. Both the effect of the sampling rate and the quantization of the measurements should be investigated mathematically to determine their effect on the data.

It should be noted that having model identification as part of the project has been very rewarding for us as students. A mechatronic engineer works in the intersection between programming, electronics and control theory and all of these have been used in the identification process. Control theory tells us how model the system dynamics, we implement the measurements on an embedded system and setup the electrical system to get the data. We have also had to use knowledge from mechatronics subjects such as Dynamics and Motion control, Mechatronics basic course and Embedded systems. It is this synergy of subjects that makes mechatronics what it is and it has been a great experience.

5.3.7 Energy dissipation

The energy dissipation is working very well considering it was made during the final part of the project. The biggest flaw at the moment is that the microcontroller can crash due to disturbances, and this can eventually be a safety hazard if the supercapacitor is overcharged to dangerous levels. More work to get rid of or handle the disturbances better is needed. Extra safety features could also be included, which prevents the supercapacitor from getting overcharged.

The power supply will rarely be used, since the accumulated energy in the supercapacitor will in most cases be enough to simulate downhills.

6 | Future Work

This section contains the largest problems that should be adressed in future projects. More specific data can be seen in the text for each part of the system.

The rules of SEM changes slightly every year and Elba has to be updated accordingly. We already know that modifications to the clutch have to be done so the ICE can idle while the car is standing still and new conventional door hinges. Additional parts definitely have to be changed as well before Elba can pass both inspections.

In its current from, the clutch is slow and also consumes a lot of power. A redesign of the clutch is recommended to increase the perfomance and reliability of the car.

Having current control for the testrig should only be considered a temporary solution. We recommend that next years team fit a torque sensor to the system to get accurate torque reading. This will also allow for a better validation of the testrig model. Having a model might be useful to design a closed loop controller using torque feedback.

The implementation of the optimization could be improved and should be validated, both on the testrig and in a real life situation. The framework exist but needs testing and iteration.

As with all complex systems, there are many small things that need improvement on the car, for example the door hinges and improving the wiring. This work has been continuous and specific details of this will become apparent as the nex years team take over the car and make their own changes. The most important part is to read the SEM rules and make sure that the car complies with them. It is the desire of the 2016 team that there will be a handover meeting with the 2017 team. It is our belief that we together can find the imprtant points to improve then.

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Acknowledgments

There have often been a sense of distance between students and faculty staff, but during this project the feeling have been the opposite, the ITM/mechatronics faculty have always been available.
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ITRL for sponsoring and housing the project.
SKF for providing bearings and actuators.
ECO2 and SHC for your sponsoring support.
We also wish to thank Shell for an excellent event and the opportunity to meet our idol Kimi Räikkönen.

Part I

Appendices

A | Rig Calculations

This appendix contains calculations made for the test rig dynamics model.

Drag force

When calculating the drag force on the car, four terms must be known. These are the air density, ρ, the drag coefficient C_D, the vertical area A and the current velocity of the vehicle, v [11]. Air density changes with atmospheric pressure and temperature, but is assumed to on average be 1.205kg/m^3 ([11] Table 2.2) in standard atmospheric pressure, 1.013kPa.

Permissable estimations for the drag coefficient of a passenger car are $0.28 - 0.37$ [11]. Elba is designed to be aerodynamically efficient so a value in the lower regions is chosen, whereby $C_D = 0.30$ is chosen.

Using geometrical methods, the area of Elba is estimated to 1.3m^2.

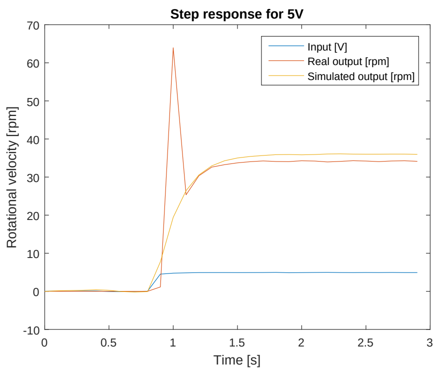
Using these values in Equation (4.3), the combined air resistance term of Elba is calculated to be $C_{tot} = 0.18$.

B | Test rig identification results

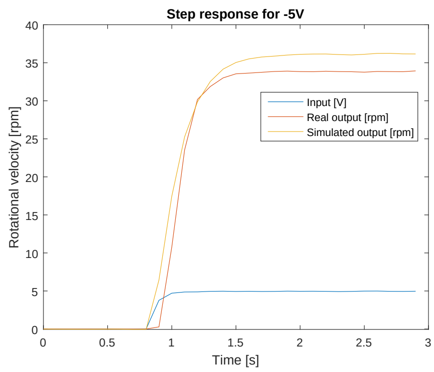
In this appendix the full results from the system identification are presented in a concise form. Positive direction is defined as the direction the rollers go when the car is simulated to travel forward. All step responses are normalized to that the measurments are positive in the plots.

Model 1

The results of the positive and negative step responses on the model without both static friction and inductance are given in Figures B.1a- B.3b.

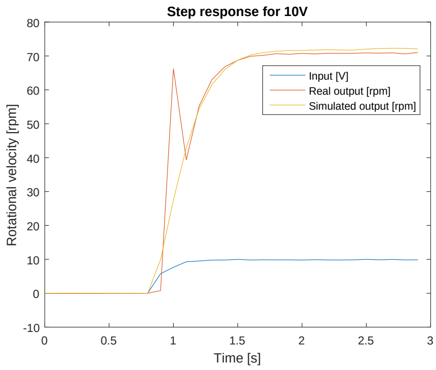


(a) 5V, positive direction.

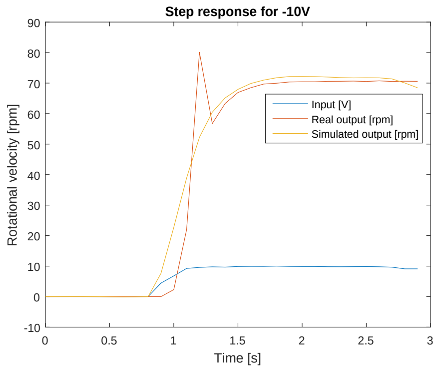


(b) 5V, negative direction.

Figure B.1: Model with no inductance and static friction, 5V step response.

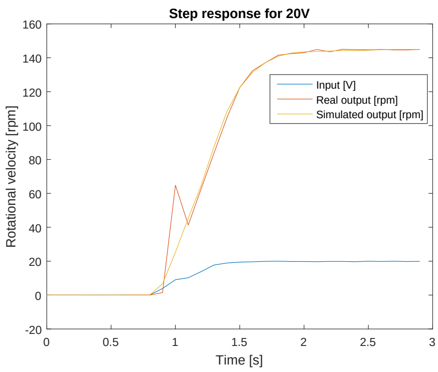


(a) 10V, positive direction.

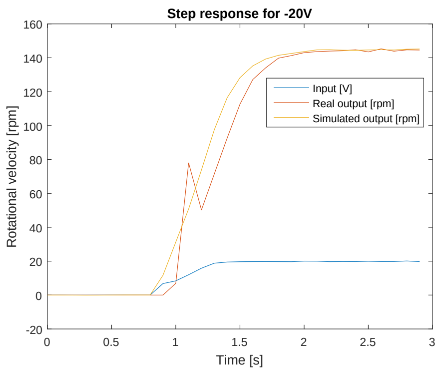


(b) 10V, negative direction.

Figure B.2: Model with no inductance and static friction, 10V step response.



(a) 20V, positive direction.



(b) 20V, negative direction.

Figure B.3: Model with no inductance and static friction, 20V step response.

In Figures B.4-B.6, sine wave responses for 2, 8 and 16 V amplitude are displayed.

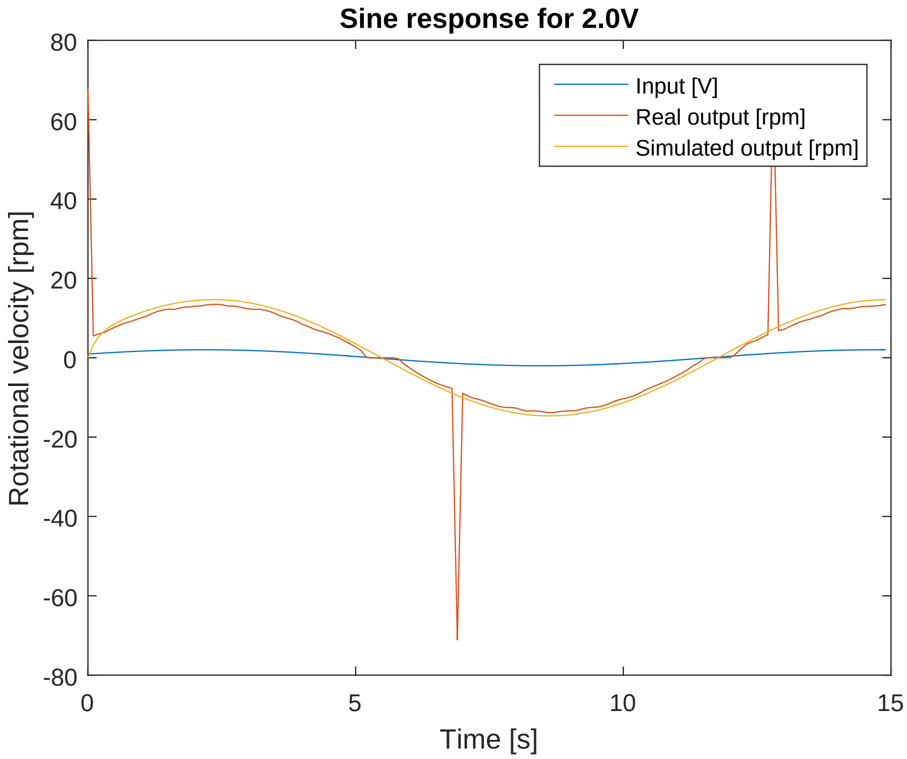


Figure B.4: Model with no inductance and static friction, 2V sine wave response.

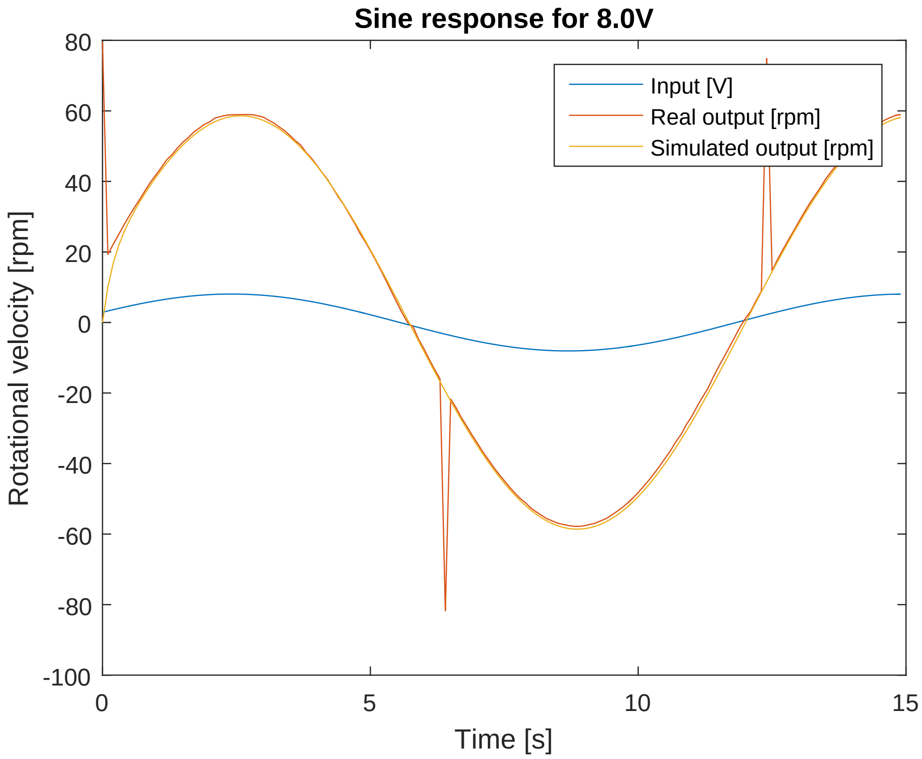


Figure B.5: Model with no inductance and static friction, 8V sine wave response.

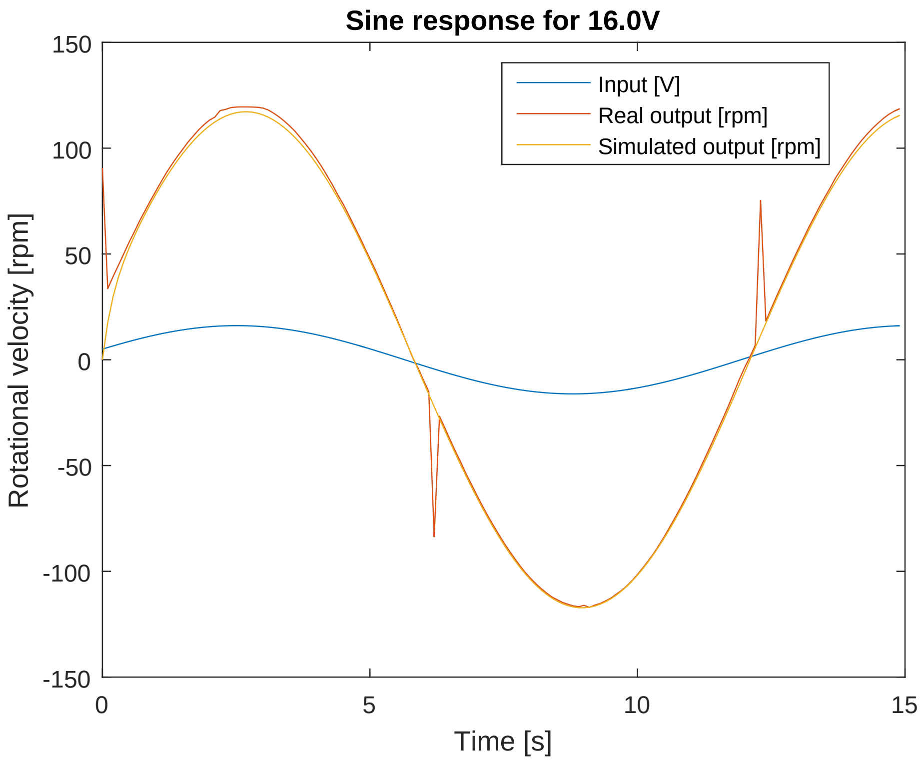


Figure B.6: Model with no inductance and static friction, 16V sine wave response.

The parameters for ths system

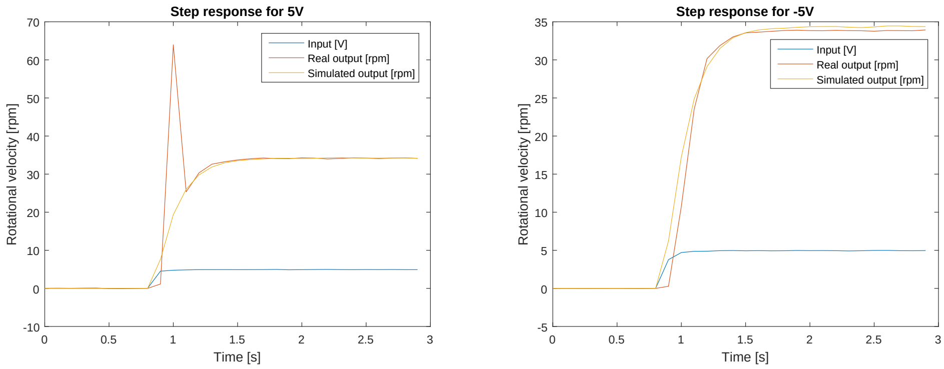
Table B.1: Parameters for motor model with no inductance and friction.

Parameter name	**Variable**	**Value**
Motor constant	k_ϕ	0.127 $\mathrm{rad\,s^{-1}}$
Motor resistance	R_A	1.9 Ω
Viscous friction	d	0.079 $\mathrm{N\,m\,rad^{-1}\,s}$
Total inertia	J_{tot}	0.015 $\mathrm{kgm^2}$

Model 2 (Final)

The results of the positive and negative step responses on the model without inductance induction and with Karnop friction are given in Figures B.7a-

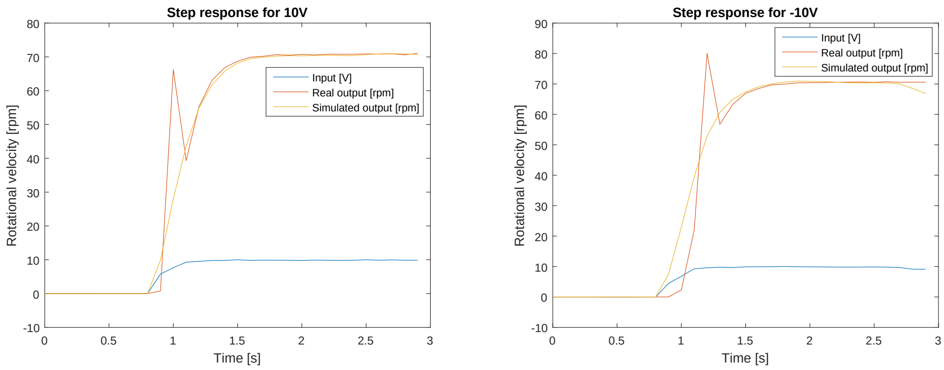
B.9b.



(a) 5V, positive direction.

(b) 5V, negative direction.

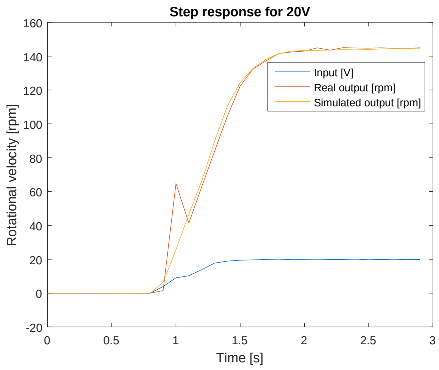
Figure B.7: Model with no inductance and with Karnop static friction, 5V step response.



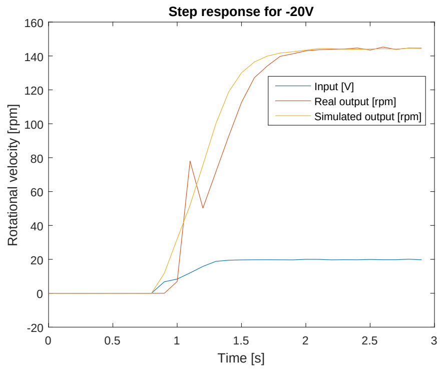
(a) 10V, positive direction.

(b) 10V, negative direction.

Figure B.8: Model with no inductance and with Karnop static friction, 10V step response.



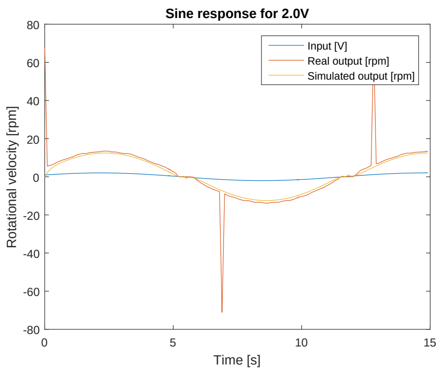
(a) 20V, positive direction.



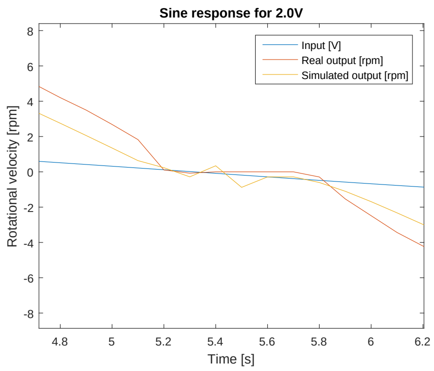
(b) 20V, negative direction.

Figure B.9: Model with no inductance and with Karnop static friction, 20V step response.

The responses to sine wave inputs are presented in Figures B.10a-B.12b.

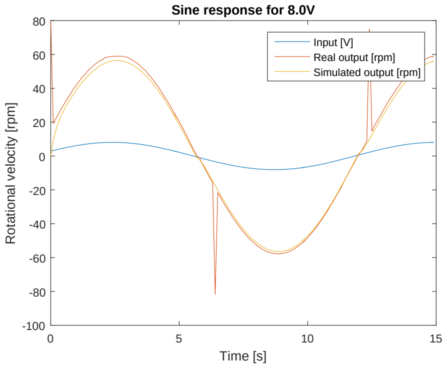


(a) 2 V amplitude.

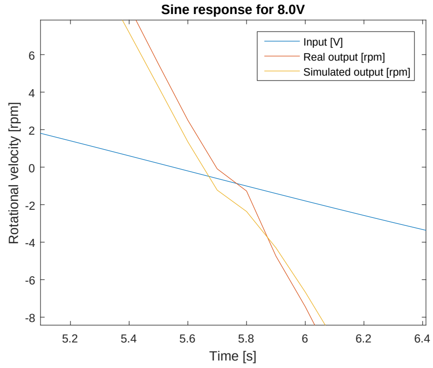


(b) 2 V amplitude, zoomed at turning point.

Figure B.10: System response to a sine wave with amplitude 2 V.

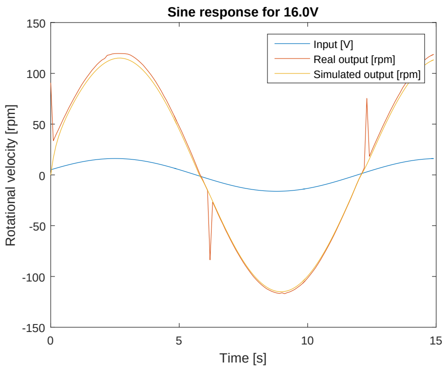


(a) 8 V amplitude.

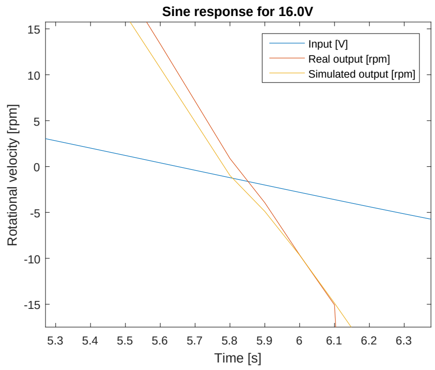


(b) 8 V amplitude, zoomed at turning point.

Figure B.11: System response to a sine wave with amplitude 8 V.



(a) 16 V amplitude.



(b) 16 V amplitude, zoomed at turning point.

Figure B.12: System response to a sine wave with amplitude 16 V.

The model evaluation requirement results are shown in Table B.2.

Table B.2: Evaluation of results for the testrig model.

Parameter name	**Step size**	**Permissable value**	**Actual value**
Steady state error	5 V	±5%	0.91%
Steady state error	10 V	±5%	0.81%
Steady state error	20 V	±5%	1.0%
Rise time	5V	±5%	3.4%
Rise time	10V	±5%	2.1%
Rise time	20V	±5%	2.1%

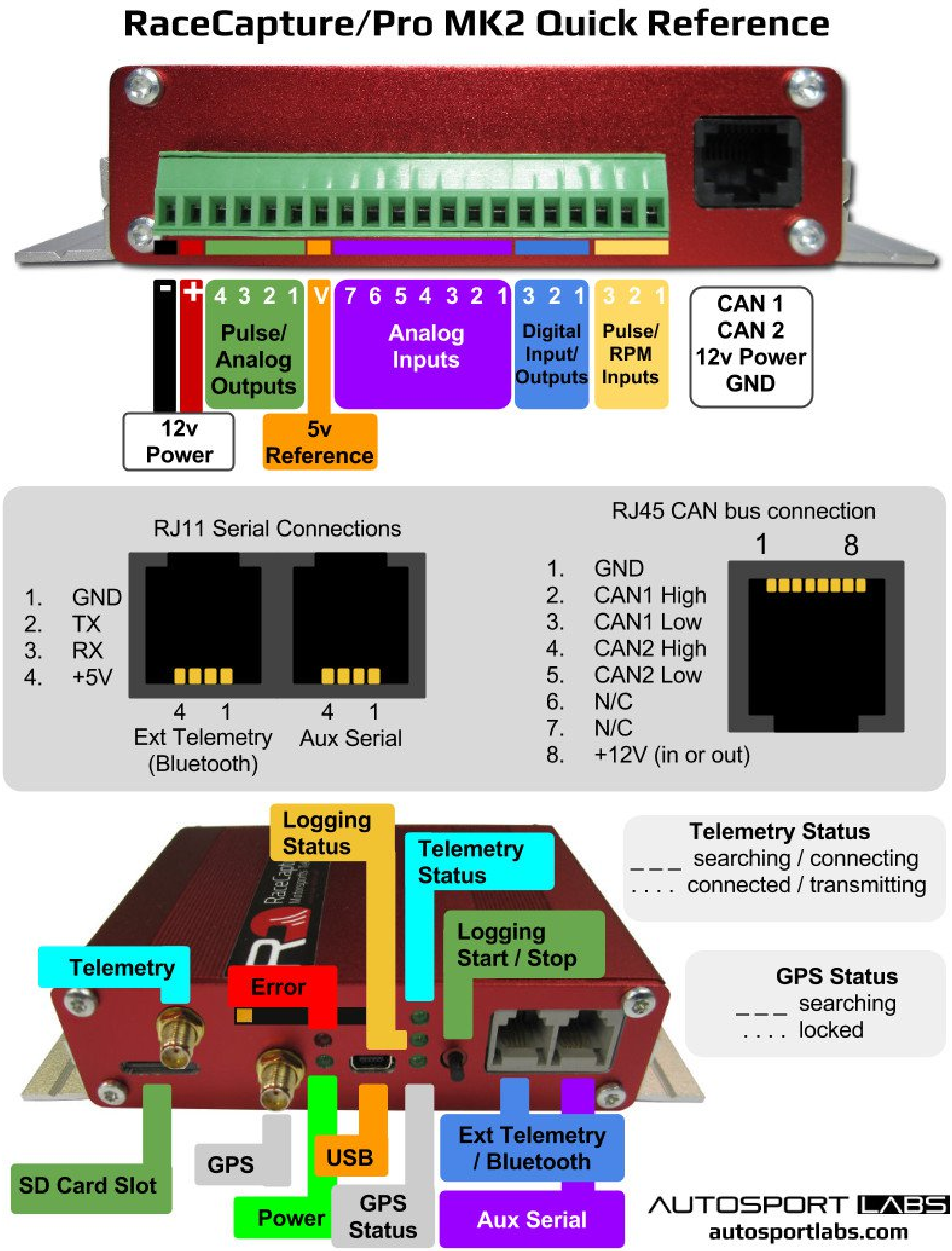
The parameters for this system are presented in Table B.3.

Table B.3: Parameters for motor model with no inductance and friction.

Parameter name	**Variable**	**Value**
Motor constant	k_ϕ	$0.127\ \mathrm{rad\,s^{-1}}$
Motor resistance	R_A	$1.9\ \Omega$
Viscous friction	d	$0.078\ \mathrm{N\,m\,rad^{-1}\,s}$
Total inertia	J_{tot}	$0.0135\ \mathrm{kgm^2}$
Coulumb friction	F_C	$0.02\ \mathrm{N\,m}$
Karnop velocity threshold	d_v	$0.01\ \mathrm{rad\,s^{-1}}$

C | RaceCapture Pro 2 specifications

The following appendix contains the quick reference guide for the RCP unit.



RaceCapture/Pro MK2 Specifications

Input / Output Channels	
Analog Inputs	

Channels	8 (battery voltage dedicated on channel 8)
Voltage range	0-5v
Input impedance	1M ohm
Voltage protection	400v (intermittent)
ADC precision	12 bit
Maximum sample rate	1000Hz
Mapping	Raw / Linear formula / Interpolated map
Digital I/O	
Channels	3
Output mode type	Open drain
Output current capacity	1A, inductive clamped
Input mode voltage range	0-12v
Input voltage protection	400v (intermittent)
Maximum sample rate	1000Hz
Timer Inputs (RPM / Frequency)	
Channels	3
Input voltage protection	400v (intermittent)
Maximum sample rate	1000Hz
PWM/Analog outputs	
Channels	4
PWM output type	push/pull
PWM output voltage range	5v
Output current capacity	50mA
Analog Output	0-5v
Voltage Reference	
Output Voltage/Capacity	5v / 1A
Connectivity	
CAN Bus	
CAN Channels	2
CAN baud rate	125K, 250K, 500K, 1M baud
CAN Termination	120 ohms terminated, both channels
CAN filters	14 per channel
Protocol support	OBDII PID (CAN 1), custom CAN messaging
Telemetry/Wireless	
Cellular (North America)	3.5G GSM 850/1900MHz (internal module, optional)
Cellular (Worldwide)	2.5G Quad-band GSM (internal module, optional)
Bluetooth	Bluetooth 2.0 (external module, optional)
Aux Serial	Type External RJ11 / RS232 signaling
Max Baud Rate	230400
Inertial Motion Unit	
Accelerometer Channels	3 (X/Y/Z) (2G, 4G capable)
Gyro	3 (Yaw/Pitch/Roll) (1000 degrees/sec)
GPS Type	External active antenna
GPS Maximum sample rate	50Hz
GPS accuracy	2.5M CEP
Storage	
Micro SD	Up to 32GB (SDHC) FAT32

Configuration Capacity	
Auto-detect track database	240
Sectors per track	20
Channel support	200
Physical	
Dimensions	5.3" (width) x 4.2" (height) x 1.2" (tall) / 135x110x31 mm(est)
Mounting area	5.5"(140mm) x 4"(102mm)
Mounting holes	Dual mounting points on 5" (127mm) centers - 0.125"-0.25" (3-6mm) fastener
Weight	9oz / 255gm (est)
Power connection	Terminal block: 1A max RJ45: 1A max
Power Consumption (max)	Main System: 0.6W With Bluetooth: 1.6W With Cellular Telemetry: 8.6W With Cellular Telemetry and Bluetooth: 9.6W
Temperature	Max Internal Temperature while operating: -40°C ~ 85°C / -40°C ~ 80°C (Telemetry module)

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D | Test rig requirements

This appendix contains the requirements used for the test rig design.

USER REQUIREMENTS

These requirements describe the problem in an abstract, high level way. They define what the user wants and are organized by goals.

The goal of the test rig is to be able to feed a test track into the rig. The car can then be put on/in the rig and be subjected to the same torque conditions as would be present on the real track.

1 Track

1.1 Track Conditions

1.1.1 Max Speed

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Alexander Ramm
Latest change date: 161220
Dependencies:
Requirement type: User
Requirement: The test rig shall be able to simulate speeds at least as high as the maximum speed needed during the Shell Eco Marathon.
Test method: Check rules, Simulink
Comment: *Accepted // AR*

1.1.2 Max Power

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Alexander Ramm
Latest change date: 161201
Dependencies:
Requirement type: User
Requirement: The test rig shall be able to provide a power to the wheels of the vehicle at least as large as the maximum power required on the Shell Eco Marathon London track.
Test method: Simulink
Comment: *Accepted // AR*

1.2 Track Accuracy

1.2.1 Accuracy Of Simulation

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026

Latest change by: Alexander Ramm
Latest change date: 161220
Dependencies:
Requirement type: User
Requirement: The test rig shall be able to accurately simulate the conditions of the supplied test track.
Test method: Simulink, test drive
Comment: *Accepted // AR*

1.3 Track Programming

1.3.1 Creation Of Track

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Adam Lang
Latest change date: 161220
Dependencies:
Requirement type: User
Requirement: For creating a track model, the user should not need to know or use any specialized software such as Simulink or Matlab.
Test method:
Comment: *Accepted // AL*

2 Physical Rig

2.1 Freight

2.1.1 Moving Test Rig

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Richard Odell
Latest change date: 161220
Dependencies:
Requirement type: User
Requirement: The test rig should be movable by 2 person.
Test method:
Comment: *Changed from 1 to 2 persons. Accepted //RO*

2.2 Versatility

2.2.1 Versatility

Status: Accepted
Author: Sanel Ferhatovic
Created date: 161115

Latest change by: Andreas Fröderberg
Latest change date: 161220
Dependencies: Max Power, Max Speed
Requirement type: User
Requirement: The test rig should be able to be used with vehicles of similir max speed and power as the Elba car.
Test method: Physical test
Comment: *Removed the term vesatility. Accepted // AF*

3 Optional

3.1 Sensor Feedback

3.1.1 Sensor Feedback

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Emil Hjelm
Latest change date: 161220
Dependencies:
Requirement type: User
Requirement: The test rig should be able to simulate and feed back sensor data to the car as on the real track.
Test method: Simulink
Comment: *Changed shall to should. Accepted. // EH*

SYSTEM REQUIREMENTS

The system requirements are a technical description of the supersystem and its subsystems. System requirements are refined from the User requirements and are organized into use cases.

1 Use

1.1 Power And Speed

1.1.1 Maximum Speed

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Sanel Ferhatovic
Latest change date: 161220
Dependencies: UR:Max speed
Requirement type: System
Requirement: The test rig shall be able to simulate speeds up to 40 km/h
Test method: Simulink
Comment: *Accepted. // SF*

1.1.2 Max Power

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Sanel Ferhatocvic
Latest change date: 161220
Dependencies: UR:Max power, SR:Power time
Requirement type: System
Requirement: The test rig shall be able to provide a power to the wheels of the vehicle of at least 1 kW during constant.
Test method: Simulink, Temperature testing
Comment:

1.1.3 Power Time

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Alexander Ramm
Latest change date: 161220
Dependencies: UR:Max power, SR:Max power
Requirement type: System
Requirement: The test rig shall be able to provide its maximum power during a time period of at least 30 sec.
Test method: Simulink, Temperature testing
Comment: *Accepted. //AR*

1.1.4 Wheel Connection

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Alexander Ramm
Latest change date: 161026
Dependencies: UR:Max power, SR:Max power, UR:Max speed, SR:Max speed
Requirement type: System
Requirement: The test rig shall be able to maintain no slippage connection to the vehicles wheels even at the maximum power and speed conditions.
Test method: Simulation
Comment: *Accepted. //AR*

1.1.5 Speed Accuracy

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Richard Odell
Latest change date: 161220
Dependencies: UR:Accuracy of simulation
Requirement type: System

Requirement: The test rig shall be able to simulate the desired speed at a maximum of 5% error.
Test method: Simulation, Physical measurement
Comment: *Accepted // RO*

1.1.6 Distance Traveled Accuracy

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Richard Odell
Latest change date: 161220
Dependencies: UR:Accuracy of simulation
Requirement type: System
Requirement: The test rig shall at all times know the distance travelled with a maximum of 5% error.
Test method: Simulation
Comment: *Accepted. //RO*

2 Model

2.1 Time Domain Characteristics

2.1.1 Model Rise Time

Status: Accepted
Author: Andreas Fröderberg
Created date: 161020
Latest change by: Sanel Ferhatovic
Latest change date: 161220
Dependencies:
Requirement type: System
Requirement: The testrig model shall have a rise time deviation of maximum 5% compared to the real system at steps of 5, 10 and 20V.
Test method: Simulation, testing
Comment: *Accepted // SF*

2.1.2 Model Rise Time

Status: Accepted
Author: Andreas Fröderberg
Created date: 161020
Latest change by: Adam Lang
Latest change date: 161220
Dependencies:
Requirement type: System
Requirement: The testrig model shall have a steady state error of maximum 5% compared to the real system at steps of 5, 10 and 20V.
Test method: Simulation, testing
Comment: *Accepted // AL*

2.1.3 Model Characteristics

Status: Accepted
Author: Andreas Fröderberg
Created date: 161020
Latest change by: Adam Lang
Latest change date: 161220
Dependencies:
Requirement type: System
Requirement: The testrig model shall show equal characteristics to the real system at a sine wave input of 2, 8 and 16 V.
Test method: Simulation, testing
Comment: *Accepted // AL*

3 Freight

3.1 Weight

3.1.1 Freight

Status: Accepted
Author: Andreas Fröderberg
Created date: 161026
Latest change by: Andreas Fröderberg
Latest change date: 161026
Dependencies: UR:Moving test rig
Requirement type: System
Requirement: The test rig shall have a maximum weight of 150 kg.
Test method: Physical measurement
Comment: *Accepted the req // RO Changed from 200 kg to 150 kg // AF*

Part II

Appended Papers

Gasoline to E100 Engine Conversion for Eco Marathon Competition

Ajay Daniel 930314-4613
Christopher Ringström 930917-7237
Hédinn Hauksson 920121-6919
Henrik Hvitfeld 920130-2552
Varun Venkataraman 900909-7792

KTH Industriell teknik och management

MF2090 – Internal Combustion Engines Project Work

School of Industrial Engineering and Management

May 2016

Abstract

Shell Eco Marathon 2016 will be held at London, the UK and KTH would be represented by team ELBA under the ethanol urban vehicle concept category. This is the first attempt with ethanol (E100) as the base fuel. The previous years' team competed with gasoline in the urban vehicle category.

This report discusses the work done by the ICE group under team ELBA and elucidates the planning, work process, accomplishments and challenges faced through the project. At this juncture it must be noted that work is ongoing to meet the larger competition goals.

The Eco Marathon project is carried out under the course "MF2090 Internal Combustion Engines, Project Work" throughout VT16.

Acknowledgements

The ICE group of team ELBA would like to thank Per Risberg, Ted Holmberg and Jack Ivarsson of the Internal Combustion Engines department, Tomas Östberg of Machine Design and Mikael Hellgren of the Mechatronics department for their continuous support and involvement through the project.

We would also like to thank our sponsors SKF, SHC and ECO2 for their support and ITRL for providing us the workspace and seclusion to develop an indigenous test rig and have a fully functional team room.

Contents

Introduction

The first task of the project was to understand the competition, its rules and regulations along with the deliverables of the ICE group. The rules and guidelines are revised each year for the competition and are available on the Shell Ecomarathon (2016) webpage (1).

The project commenced with inputs from the previous ICE group as we were inheriting their vehicle and work. Suggestions were made to utilize the existing engine (Honda GXV 57) with drivetrain and focus on mechanical and control improvements.

Key points from 2015 engine group:

- Engine might be underpowered
- 1 point optimization carried out at 3000rpm full throttle
- Robustness of connectors and harness must be improved
- Attempts of coatings unsuccessful
- Optimization of engine damper and flywheel is required
- Raising the compression ratio requires reasonable time and effort

These points provided a basic idea of the project and the possible difficulties that we would face.

Test Rig

To be able to perform tests with different load cases and different engine speeds, a test bench had to be developed. To load the engine, the test cell from previous year relied on a 3-phase asynchronous motor connected to a resistor pack of 144 Ohms. The asynchronous motor was managed through a frequency controller (VFD), which made it possible to adjust the rotational speed of the electric motor. Further, this motor was connected to the combustion engine with a driving chain, as can be seen in figure (1).

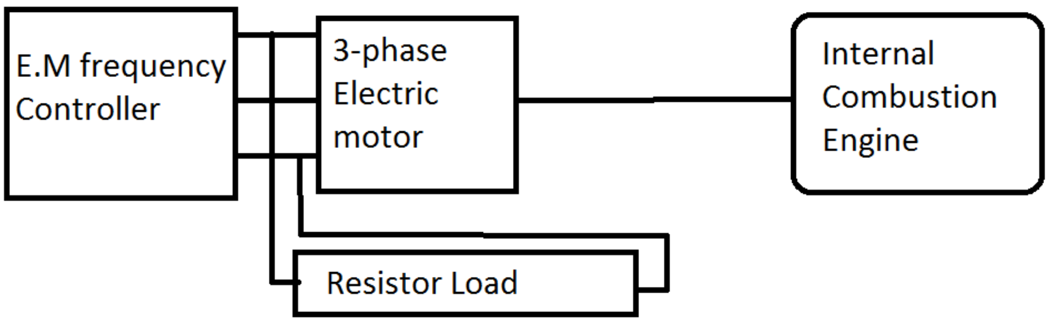

Figure 1 Schematics of the test rig

By demand from the school, the previous year´s test rig was not sufficient, mainly because of the safety issues with the test rig and the engine test engineer in the same room. With the motivation to eliminate issues like carbon monoxide poisoning and danger of moving parts coming loose, a new test rig had to be developed. The foremost tasks were

- control speed and load of the combustion engine externally
- Use the test rig for the coming year´s Eco car project
- Acquire data from Engine-runs in terms of different ambient and tuning parameters
- Handle the test procedures of the Engine for this year, as well as being modular enough for other engine types
- Mount auxiliary systems securely, i.e. Engine Control unit, Fuel supply, data acquisition system and ignition control

The different tasks were taken into account when designing the new test cell together with the rig.

Safety and Robustness

As mentioned, safety was a big issue from the previous year. It was decided to mount the test rig in another room, next to the old test room. The old test room was rebuilt entirely as a control office with computers. To monitor the actual test rig, a web camera was mounted in the new test room.

Further, to reduce the vibration caused by the ICE, it was decided to use rubber mountings in the new rig. This reduced both noise and vibration excitation in the electrical systems, as well as movement of the rig during tests.

Flexibility

The Engine test rig had to be easy to use with different engines and types to be useful in the future. This resulted in an engine test rig that is able to run engines with the output axle in both horizontal and vertical direction, and at the same time enable mounting engines with different mounting configurations.

Construction

The final test rig was constructed using CAD modelling for fast realization and visualization during the design phase. This means that the demands could be evaluated directly in the CAD-model. The resulting CAD-model of the base of the test rig can be seen in figure (2)

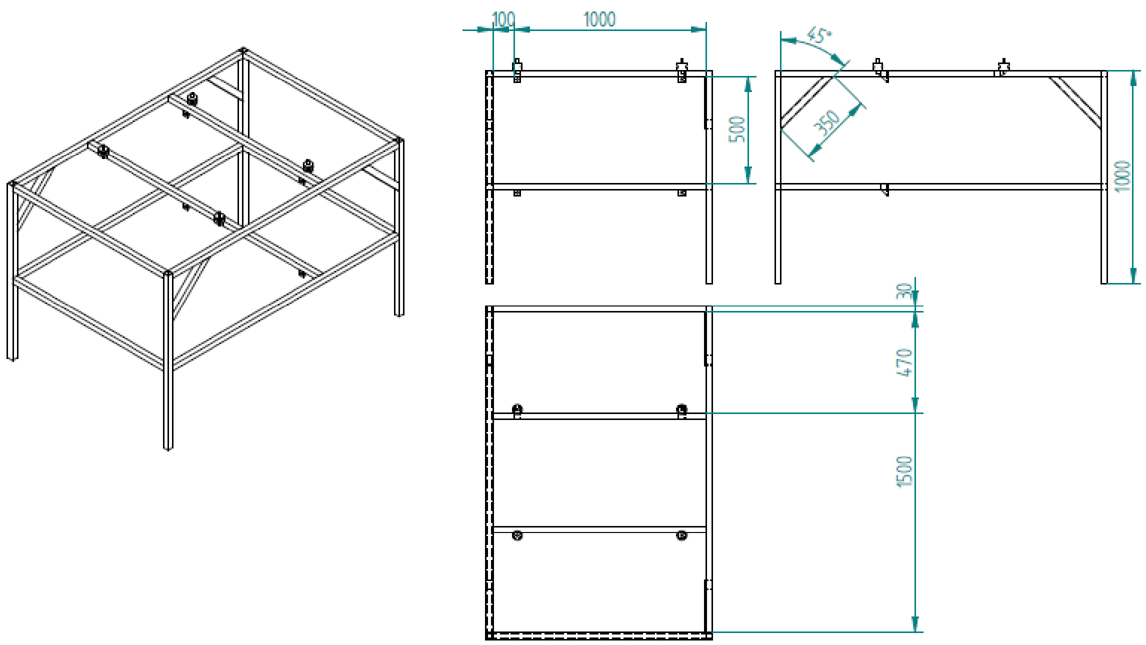

Figure 2 Blueprint of the base of the test rig

The choice of construction material was chosen to be steel in 30x30x1.5 square profiles. The choice was steel SS-EN- 50 100 mainly because of the low sensitivity to fatigue and reasonable tensile strength. To minimize the reduction of strength during welding, the test rig was mainly TIG-welded to have good control over the weld.

Although no calculations were made, based on experience from the previous year's rig, the dimensions were believed to be enough for small engines typically used for these projects.

As can be noted from figure (1), the lower base consists of a table with welded mounts for rubber couching, which can be mounted in a vertical or a horizontal matter. The upper part of the test rig can be observed in figure (3). To reduce the risk of the chain jumping off the sprockets on the electric motor and the engine, the upper module was constructed in one piece, with the electric motor and the engine firmly mounted on the module. This allows for lower moment of the engine in relation to the electric motor and therefore low variation in chain tension during running. The upper module is connected to the base with rubber bushings to reduce vibration transfer into the base. This reduced the risk of the rig moving during operation and further reduced the vibration onto the electrical equipment.

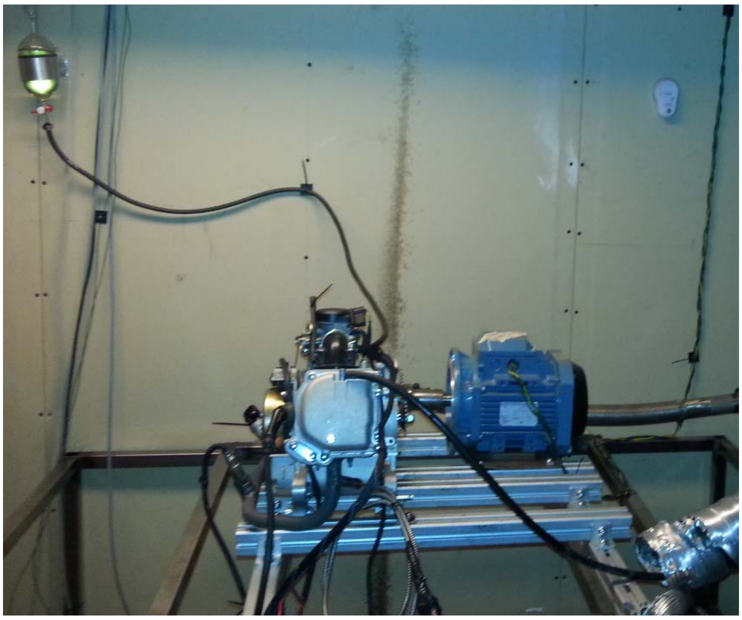

Figure 3 Electric motor and ICE mounted on the upper module of the test rig. Fuel supply system is in the upper left corner and CO sensor in the upper right corner

To mount equipment on the test rig, a mounting plate was introduced. This gave a surface for mounting the log-equipment, fuel supply system, engine control unit, lambda sensor unit and main relay. The main relay was used to enable the rig to be remotely shut on/off as a safety measure. The mounting plate also gives the equipment a protection in the event of parts braking loose from the engine.

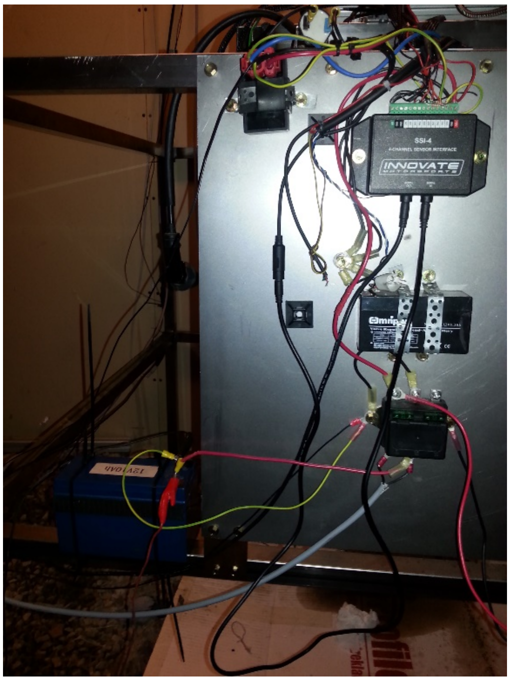

Figure 4 Mounted logging equipment, ignition system, relay and battery.

Engine Logging

The ability to save data during test rig operation is an important feature that would provide visualization of transient behavior and log data for different engine speed and load settings. This enables the operator to make adjustments based on calculations with less runs and more precision thus giving the user a cheaper, faster operation with less chance of failure. This reasoned the need for a data acquisition susyem.

Choice of System

The choice was a data log system called Innovate SSI-4. The SSI-4 has the ability to log four different sensors, including RPM. It also has the provision to log lambda as an external serial input therby creating a log system of 4 analog inputs and 1 serial. The serial schematic setup is depicted in figure (5)

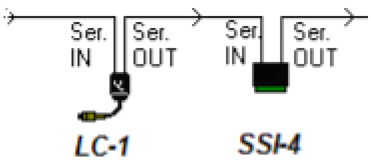

Figure 5. Schematic of logging equipment setup and connections

The analog setup is depicted in figure (6)

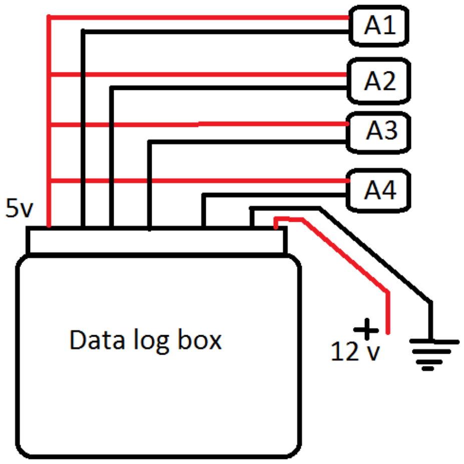

Figure 6 Analog setup of SSI4 logging boxdriven by 12V and measurement signal from 0-5V

Sensors

The sensor setup for the log-system was chosen to log the ambient conditions and the engine conditions in parts. The ambient conditions are interesting as a change in ambient temperature and pressure will act as an external disturbance to the system. In this case the ambient temperature is the most interesting as the ambient temperature has the biggest range of change and will have an important effect on the engine operation. The barometric condition was evaluated as low range because of the local height over the sea at Stockholm and London (race location) differs very little. Further, in the test cell, the ambient temperature may vary a lot during operation because of the heat from the engine itself. This means that during operation the temperature may affect the intake air density between runs, and thus affect the air fuel ratio.

The internal log options were chosen as follows:

- Lambda (serial)
- Engine oil temp (analog)
- Exhaust temp (analog)
- Engine speed (analog frequency)

The lambda is the most important factor for this as it tells the air fuel ratio and thus gives the most information of the actual condition of the engine. Further theengine oil temp has an important effect on cold running conditions. The exhaust temperature is mainly interesting as a measure to reduce fail risk and is reflective of combustion efficiency. The engine speed is chosen mainly because it will inform the test rig engineer where the operation point of the engine was during each point in time.

This will be described in greater detail under the Engine Control Unit section of this paper.

Hardware

System Requirements for E100

One of the primary tasks was to understand the needs of an E100 engine and to evaluate the possibility to use the existing engine setup for the task. The previous team had procured 3 engines wherein one was a spare, one was modified and the third mounted on the vehicle in 'ready-to-drive' condition. The modified engine was disassembled for studying the engine construction and feasibility for design modification.

Typically the requirements for a gasoline engine when converted to run on pure ethanol (E100) are:

- High compression ratio (~13:1)
- Turbocharging/boosting
- Direct injection system
- Ignition timing control

The following references are recommended for pure ethanol engine design (2) and gasoline engine modification for E100 (3).

While 'turbocharging' and direct injection are prohibited by the rules in the current edition of the competition, increasing the compression ratio and enabling ignition timing control were considered possible to execute and were included in the ICE group deliverables.

Engine Choice

Inspection of engine used 2015

The engine that was chosen and used by the internal combustion team Elba 2015 was the Honda GXV57. It was inspected and its features were documented in an early stage to decide whether to use the same type of engine again or whether to seek for another type. The Honda GXV57 is a 57 cc single cylinder engine with over-head valves. One significant disadvantage with this engine was its vertical shaft as this resulted in the use of a bevel gear. The bevel gear did not only reduce the overall efficiency, it also broke repeatedly. It was thought to be the torque peaks and vibrations from the engine that the bevel gear could not handle.

Since the bevel gear had caused many problems for the previous year's team, the idea of mounting the engine so that its output shaft would be horizontal was evaluated. The problem with such an action would be the risk of too little lubrication to the different components in contact, especially the piston rings sliding against the cylinder wall. It was found that the engine has a plastic gear that splashes oil inside it. This can be seen in figure 7. It would not function properly if the engine was to be tilted and an external oil pump would then probably be the best option for guaranteeing proper lubrication.

Figure 7. Plastic gear for oil splash lubrication inside the engine

The over-head valves are positioned vertically into the combustion chamber which can be seen in figure 8. This was regarded as a limitation as trying different injection angles for possible gain in efficiency would be difficult. Further, the cylinder head and the engine block was cast as one piece. This reduces the possibilities for increasing the compression ratio through shaving off the cylinder head and generally limits modifications of the cylinder head.

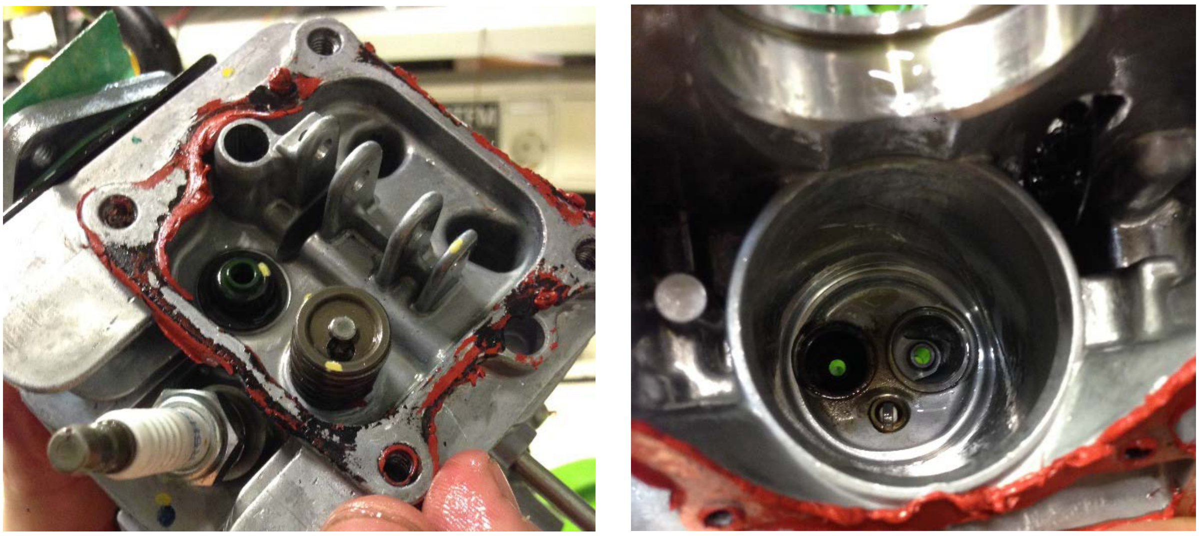

Figure 8. Valve position in the cylinder head of the Honda GXV 57

To increase the compression ratio, last year's team tried increasing the height of the piston through welding which turned out to be difficult without getting porosities in the welded material. They also tried manufacturing longer connecting rods but did not have sufficient time for verifying if the outcome was an improvement. However, it was found during the disassembling that one of the bolts connecting the connecting rod to the crank shaft was in contact with the crank shafts sliding surface which is not favourable for durability. It was therefore clear that increasing the compression ratio can be complicated and aiming for simplifying the possibilities was a priority.

The engine uses push rods with rocker arms for opening the valves wherein the push rods are pushed by one plastic cam lobe. This is also a limitation for changing the timing of the engine.

The drawbacks with the old engine are listed below as a result of what was found during the inspection:

- Low compression ratio
    - The GXV 57 has a compression ratio of 8:1 (4)
    - Previous team had tried to make mechanical modifications to increase the compression ratio (such as increasing the piston crown height by welding) and increasing connecting rod length but these techniques did not bear fruit
    - The engine had a single plastic cam lobe and the valves were pushrod actuated making valve timing modification a challenge
- Fixed ignition timing
    - The engine had a TCI ignition system with fixed timing
    - The previous team did not develop a timing control unit which is essential for E100
- Engine mounting and drive
    - The engine had a vertical driveshaft which necessitated a bevel gear leading to additional losses and increased weight
    - The engine mounting bracket was complicated and large thereby adding to the overall vehicle weight
    - Engine damping was considered ineffective
- Unibody construction
    - The GXV 57 had an inseparable cylinder head and block rendering compression ratio modifications difficult

After completing the evaluation of the GXV 57 and the needs of E100, it was decided that a new engine would be chosen. The major criteria for new engine selection were:

- Naturally high geometric compression ratio
- Horizontal driveshaft
- Modifiable and availability of spare parts
- Modern engine construction
    - Fuel injected
    - Overhead camshaft
    - Force feed lubrication for mounting flexibility
    - Match torque output of optimized GXV 57
    - Ignition control capability

Based on the selection criteria, the following engines were shortlisted:

Engine	Fuel System	Compression Ratio	Peak Torque, Nm	Horizontal Driveshaft
Yamaha Neo's 4	Fuel Injected	12:1	3.15 @7000rpm	Yes
Honda NSC 50	Fuel Injected	10:1	3.53 @7000rpm	Yes
Honda GXH 50	Carbureted	8:1	2.7 @4500rpm	Yes
Honda GX 25	Carbureted	8:1	1 @5000rpm	Yes
Viarelli GY6	Carbureted	10.3:1	2.8 @7500rpm	Yes

The technical specifications of the listed engines may be referred from (5), (6), (7), (8) and (9).

While the Yamaha Neo's 4 and Honda NSC 50 engines were the most advanced and favored, due to sourcing issues we decided on the Viarelli GY6 which is a Honda based 50cc motor design from the 1980s.

Although this motor is dated, it provided a good match to our new engine criteria and since price, sourcing and spare parts were not an issue we decided on the GY6. 3 motors were ordered along with a set of spare parts which included the cylinder head with valve train, performance camshaft, crankshaft with connecting rod, head and exhaust gaskets and piston with pin and rings.

To summarize the strong points of the GY6:

- High natural compression ratio
- Separate head and block construction which enables further compression ratio increase
- Overhead camshaft provides opportunity for valve timing and lift modifications
- Forced feed lubrication (gerotor pump) provides engine mounting inclination flexibility
- Easy to source engines and spares from within Sweden

GY6 Engine Construction

Upon receiving the new engines, one engine was disassembled for a construction study and considerations required for mounting the engine on the test rig, on the vehicle and the drive sprocket mount on the crankshaft were evaluated.

The GY6 is a moped engine and hence the engine body is cast along with the swingarm which houses the CVT. The first step was to separate the transmission portion which was not of interest for the project. The engine was available with a starter motor and after discussing with the mechatronics group, it was decided not to use the starter motor as it would be redundant. Engine cranking would be performed by the big BLDC motor as was in the previous year.

The engine had a simple construction with 2 over head valves which were rocker driven by an overhead camshaft.

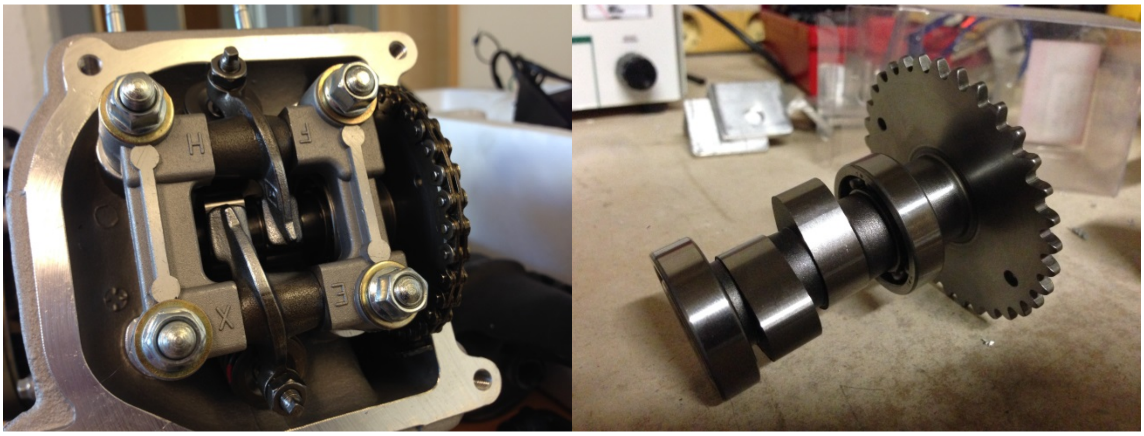

Figure 9. Valve rockers and performance camshaft of the GY6

The valve timing and maximum lift were studied. The maximum lift of both the valves was 4.5mm. The valve timing is given as follows:

Intake		Exhaust		Overlap
IVO	16.97° BTDC	**EVO**	16.28° BBDC	66.26°
IVC	50.65° ABDC	**EVC**	49.29° ATDC	
Duration	247.6°	**Duration**	245.6°	

BTDC-before top dead center | ATDC-after top dead center

BBDC-before bottom dead center | ABDC-after bottom dead center

It is observable from the camshaft that the lobes are identical and hence the valve timings too must be identical. The deviation in timings can be attributed to error in measurement.

The engine has a HEMI combustion chamber with a curved piston crown. The rings are standard 3 piece set with two compression rings and one 3 piece oil control ring. The connecting rod is unibody with a semi-floating piston pin.

The cylinder head and block portions were separable and measurements were made for determining maximum thickness that could be removed in order to increase the compression ratio from 10.3:1 towards 13:1 while considering the dynamic valve-piston clearances. Paper impressions were used to approximate the clearance volume.

Intake and Fuel system

The intention was to use the same fuel injector that was used the previous year; the injector of the Honda Zoomer. The previous team did not have any problems with the injector and since our application is similar, the fuel injector was thought to be suitable despite the change of fuel. The advantages of using an injector is that the volume of injected fuel per cycle can be controlled by changing the injection time duration. Also, the injection timing, at a certain crankshaft position, can be controlled. These two parameters are useful for improving efficiency as fuel and air mixing can be improved and the lambda value can be kept at a set value in real time. The injector together with the previous year’s injector mount can be seen in figure 10.

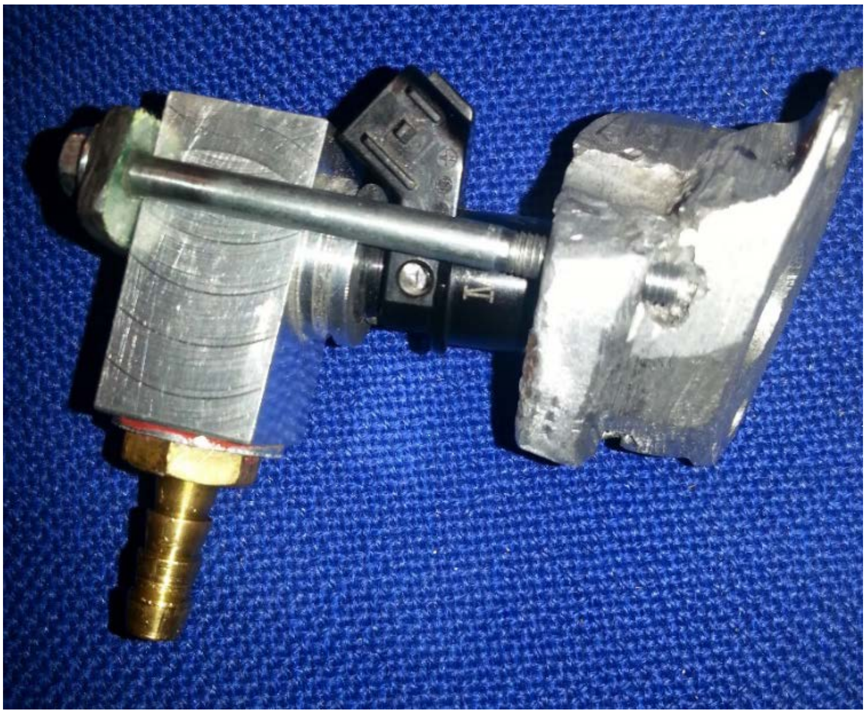

Figure 10. Honda Zoomer injector used by the previous team coupled to a handmade intake manifold.

However, as a first step the original carburettor was used for running-in and mapping of the engine in the test rig. The carburettor gave a few problems in the beginning. At first, the fuel tank was situated at a lower level to the ground compared to the carburettor and was therefore pressurised for the fuel to flow into it. Even though low pressures were used, the carburettor flooded. The fuel tank was therefore moved to a higher level to avoid this problem after a number of different attempts with lower pressures. Further, the air/fuel-ratio can be adjusted on the carburettor and it was found that the ordered ones were not pre-set by the manufacturer. Therefore adjusting the carburettor is recommended to make sure it was working properly.

At first a simple mechanism was built to enable throttle opening at five different positions for an initial mapping and testing of the engine in the test cell. The toolbox in Matlab that was used for setting up the engine tests for mapping of the engine required more precision of the throttle positions and therefore a more precise mechanism was built for that purpose.

An interface was welded together to enable mounting the injector and throttle body to the intake of the cylinder head. This can be seen in figure 10. Further, the flow rate of the injector was also measured using gasoline to verify that the flow rate would be enough. The fuel line was pressurized up to 3 bar (max. allowed pressure) and the injector opened. The time it took to inject 100 ml of fuel was measured and that yielded a flow rate of 36 cc/min which would be sufficient for 3.66 hp at the crankshaft output according to (10).

ongoing work involves mounting the injector onto the engine to test it together with the new ECU. The next step is to fabricate a throttle body and then mount it together with the injector. According to the competition rules, the engine has to have an idle mode which necessitates THE presence of a throttle body. The intention is that the throttle shall have two states, fully open and idle.

Exhaust System

An exhaust system was built from existing piping at ITRL. A complete engine of the same kind (GY-6) was found in the storage room and the exhaust pipe was taken from there. The muffler was removed and the pipe was cut down to a desired length after which mounts for the lambda sensor and the temperature sensor were welded on.

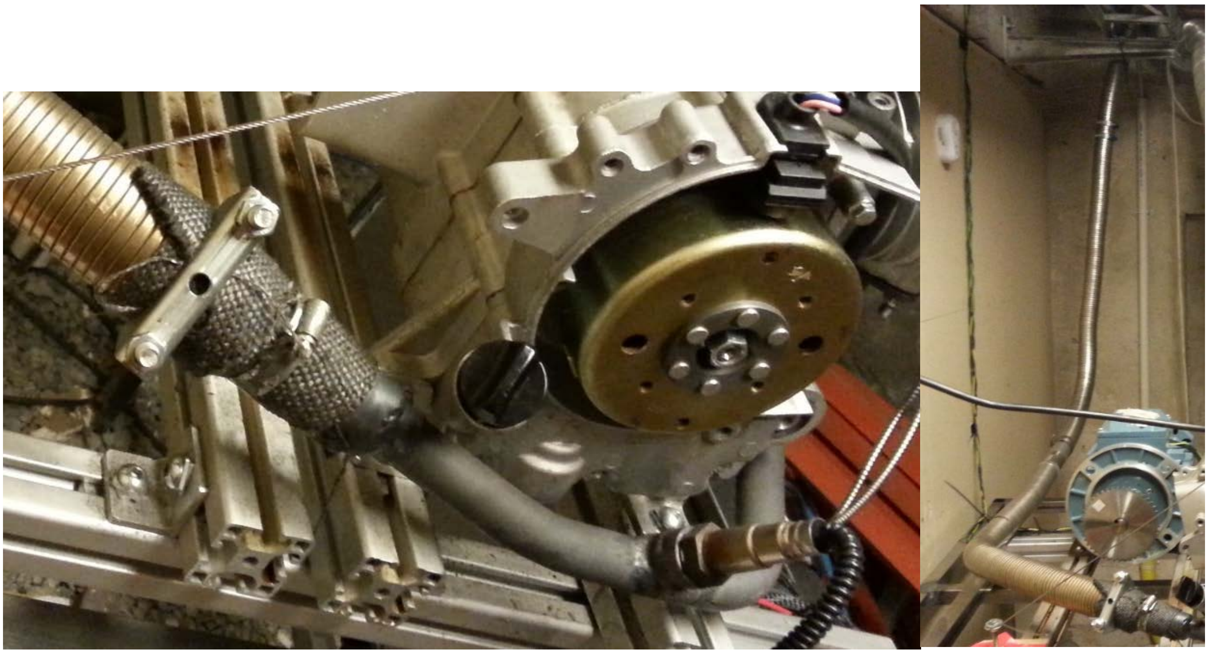

Figure 11. Exhaust system setup on test rig. An interface was welded on the exhaust to fit into the flex pipe. The interface was insulated with fire resistant blanket and hose clamps. The flex pipe leads to the outside of the building through a hole

To evacuate the exhaust gases from the test cell, the piping and exhaust fan from last year were used. The fan did not work efficiently enough and the CO sensor in the test cell went off repeatedly. This lead to a big headache (literally). A solution needed to be found quickly to this problem and it was decided to insulate the exhaust better and lead it all the way to the exhaust vent of the building using flex pipes. This worked better and the final setup of the exhaust system can be seen in figure 11.

Encoder

An encoder was mounted on the engine via a belt and pulley assembly to enable crankshaft position monitoring. The encoder of the previous team, Yumo E6B2-CW3En was used with new pulleys that were ordered from Aratron in Solna. This was due to the avialable pulleys being too small to fit on the crankshaft and keep the same reduction, 2:1.

The two pulleys from last year had 20 teeth on the engine crankshaft and 40 teeth on the encoder respectively, but the new ones have 30 on the crankshaft and 60 on the encoder. The engine rotates twice for every rotation of the encoder. The encoder produces 1024 pulses/rotation plus an index pulse for every rotation which can be used for the TDC reference. It also produces a 90° out of phase pulse to determine the direction of rotation.

To mount the encoder onto the new engine a bracket was built from aluminum. The smaller pulley was bored out so that it could fit onto the 14 mm diameter crankshaft portion and a threaded hole was made through the pulley so that it could be fastened to the shaft. An adapter was made for the bigger sprocket since its 8 mm hole was too big for the 6 mm diameter axle on the adapter. The adapter was press fitted to the shaft so a screw was not necessary. To tension the belt, a hole was drilled on the bracket and then the bracket was mounted. The belt was tensioned to desired tension and a new hole was made on the bracket. The setup of the encoder can be seen in figure 12.

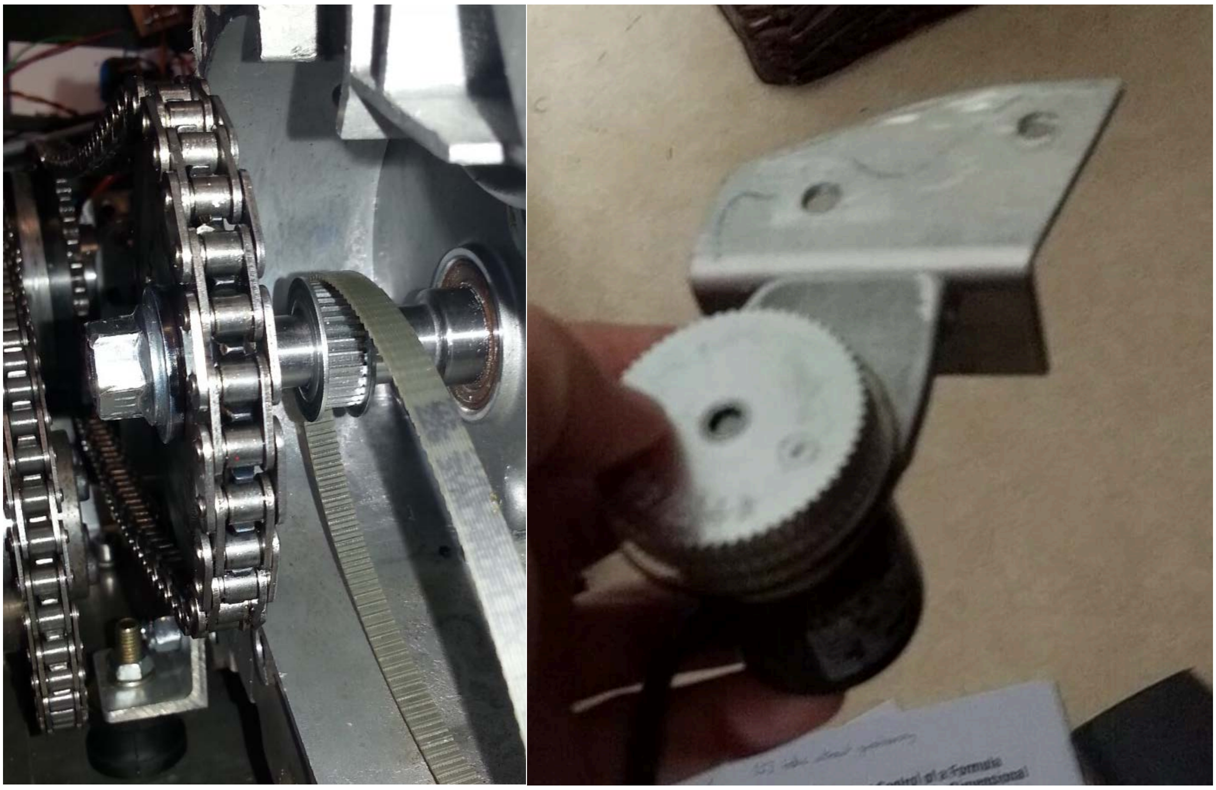

Figure 12. Encoder setup. To the left, pulley and belt mounted on crankshaft on the output side of engine. To the right, encoder mounted on bracket which was bolted on engine

Engine Drive Sprockets

To enable power transfer from the engine to the drivetrain in the car, a chain would be used to be able to use last year's drivetrain. For this to be possible a new sprocket needed to be fabricated since the interface between the previous engine and the new one with the drive sprocket was different. For simplicity and to keep the same gear ratio, an adapter was welded to the old sprocket as well as removing some extra material to save weight. This adapter was taken from the new engine since it had the same splines as on the crankshaft.

The same applies to the test rig, a new sprocket would have to be made in order to use last year's electric motor. An adapter was also made for that sprocket to maintain the same gear ratio. Both sprockets can be seen in figure 13.

 

Figure 13. Two sprockets made for the new engine. Left: Sprocket connecting ICE to electric motor on the test rig. Right: Sprocket connecting ICE to drivetrain in vehicle with chain

Compression Ratio

To increase the thermal efficiency of the combustion engine, the compression ratio was increased. The original compression ratio was 10.3:1. The goal of the modification was to have a compression ratio around 13:1 to utilize the knock resistance capability of ethanol and have good efficiency. To adjust the compression ratio, first the combustion chamber volume had to be calculated. With 50cc stroke volume, the calculation gives:

$$\frac{(50+x)}{x}=10.3$$
$$50/9.3=x=5.37$$

Where *x* is the combustion chamber volume. To have a compression ratio above 13:1, the volume had to be reduced to

$$50=x(13-1)$$
$$x=4.16$$

To know how much the compression ratio could be increased, the combustion chamber was measured using wetted paper. It was possible to measure the piston-to-valve clearance. The measurement was done in cold conditions, and was about 2.5 mm. Based on this knowledge, the decision to reduce the deck height by 1 millimeter. With a bore of 39 mm, the compression ratio increased to

$$5.37-\frac{3.9^2}{4}\pi\cdot 0.1=4.175$$
$$\frac{50}{4.175}+1=\varepsilon=12.976\simeq 13$$

where ε is the compression ratio. This means an increase in theoretical thermal efficiency of

$$1-\frac{1}{\varepsilon^{\gamma-1}}=\eta$$

$$\frac{\eta_2}{\eta_1}=\frac{1-\frac{1}{\varepsilon_2^{\gamma-1}}}{1-\frac{1}{\varepsilon_1^{\gamma-1}}}=1.057 => 5.7\%$$

From the standard compression ratiocompared to the old enginewith 9:1 compression ratio, the increase in thermal efficiency is 10.3 %, not regarding eventual difference in the combustion chamber form. Further, the reduced deck height decreases the squish height, pushing flow towards the center of the combustion chamber thereby creating turbulence and reducing end gases volume on the opposite side of the spark plug. This should further increase efficiency and is to be seen as an additional advantage.

Camshaft Modifications

The fact that the engine has an over-head cam shaft offers the possibility of changing the valve timing for improvements in efficiency and was therefore regarded as a significant advantage with the GY6. The option of modifying the profiles of the lobes of the cam shaft was therefore evaluated. For a company to professionally grind the cam shaft, much time is required and many parameters are needed including exact profile of the original shape of the shaft and the desired shape. The option of milling the lobes was not a possibility as the shaft has been hardened and might destroy the blades of the milling tool. Therefore, the workers at the production department did not want to offer their NC-mills for that purpose. A proposal for the next year’s team is to evaluate the possibility of grinding the cam shaft at an early stage and contact a company with the right capability of grinding it. If enough time is available, changing the profiles is definitely possible and can give much gain in fuel efficiency.

Drivetrain, Engine Mounting and Operation Cycle

The existing drivetrain architecture which provided a parallel hybrid capability was retained. The engine mounting location was to be conserved and new engine mounts were developed which largely simplified the mounting approach. L-bracket mounts (figure 14) which were used from last year’s test rig were carried over to the new rig and it was decided to use them for the engine as well.

The brackets have dramatically reduced the engine mount weight from the previous year and with the elimination of the bevel gear it can be said that the engine and mounts together have provided weight saving, although this has not been quantified. The dampers for this year are larger at 30mm diameter and 25mm thickness from the previous year with M8 bolts for fastening. The mounting on the vehicle side was enabled using helicoils on the baseplate.

For the operation cycle, a popular amongst participants in the EcoMarathon is the pulse and glide (10) otherwise known as the coast and burn technique. The merits and demerits of this strategy were discussed and the major limitation of the application of the strategy this year would be the varying elevation of the track. As previous races were performed on flat tracks, the application of the technique was straightforward. This is a simple yet effective strategy for fuel efficiency boost and could be considered in full or part to be implemented in the overall drive cycle depending on the track conditions.

Figure 14 New engine mounts and damper

Engine Control Unit

An ECU from the previous year was inherited with this project. This ECU was a closed loop PI-controller of lambda. The PI-controller utilizes the broadband lambda sensor for feedback and adjusts the injector opening time accordingly. The reference value in the inherited controller is taken from the CAN-bus, and is normally set in the back ECU, the master for the driveline. The ECU is based on an Arduino Duo with 32-mbit ARMm processor.

To be able to start the engine at cold conditions, this was not sufficient for our case. As the whole project had focus on the future, and to be able to hand over a product with the ability to modify and further develop, a focus was set to build a complete engine ECU with open and closed loop control of fuel, ignition timing as well as being robust, as the previous controller had problems with the injector opening when the signal was not given. At the time of writing, the work with the ECU is in progress.

PI Closed Loop Control

The PI-controller from last year will be kept as it had been working with good results according to last year's team. This also means that the Encoder input from last year's ECU will be reused. The encoder has a 2:1 rotation ratio, that is, the combustion engine rotates two rotations during one rotation of the encoder. Using z-phase as TDC marker and A-B phases as counters for the rotation, it is possible to directly determine the position for one 4-stroke cycle and thus control injector opening angle. The controller layout can be seen in figure 15. Notable is the reference value directly taken from CAN-bus. Further, a safety feature for voltage above 5 volts is introduced to save the processor during operation. This essentially means that the combustion engine will be shut off if the lambda controller would give a too high voltage. To avoid this, open loop is introduced.

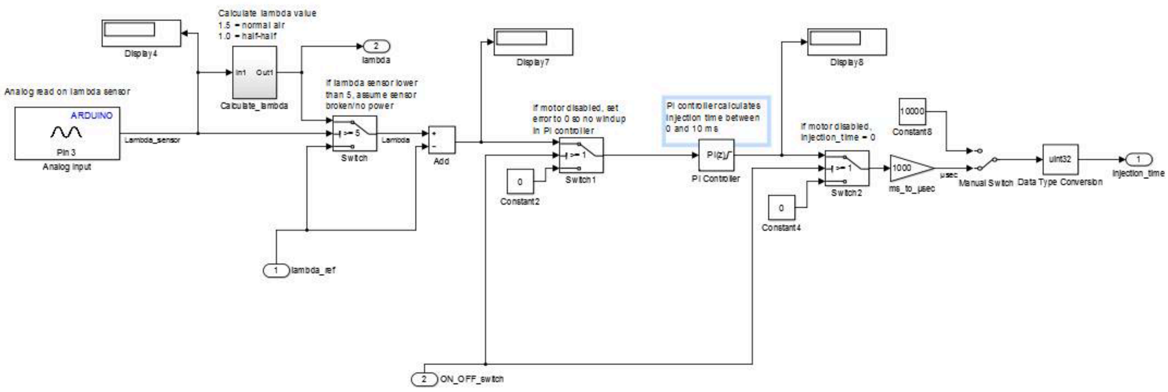

Figure 15 Model based programming is used for the ECU; this figure shows the basic setup for the PI-regulator controlling the fuel for the engine

Ignition Angle Control

One important factor for modification was controllable ignition angle. This feature makes it possible to increase the maximum efficiency of the engine further, as well as reduce ignition angle during operation if knock (detonation) occurs. To implement this feature, the code controlling the injector opening angle and opening time is utilized. The control of the ignition coil is very similar. Instead of opening time, the ignition coil is charged during "dwell time". Dwell time is a function of the voltage over the coil. The coil functions as a transistor, i.e. the coil is fed with constant 12 volts and ground, and the base is grounded (Low) during the dwell time. When the coil is charged, the spark will jump over the electrodes at the spark plug.

As the control of the ignition coil is very similar to the injector with open loop ignition angle, but with open loop values of dwell time, the code could be reused with different outputs of the microcontroller.

The ignition coil that will be used in the project is a BREMI 11 856. Made for passenger cars it allows for high spark energy during operation. This results in the ability to use higher electrode distance in the spark plug, which is beneficial for lean combustion. The dwell time at 12 volts for the specific coil is 2.5 ms.

Figure 16 Picture of the ignition coil type

To control the spark angle, the ignition angle uses a 1-D look up table, with engine speed as input. The operation principal of the combustion engine is full load during operation, which means that other points of load other than full will not be reached. An exception is idle, but the reasoning is that the combustion engine will not be used for propulsion during idle rpm and only on full load. Thus, the 1-D ignition table is sufficient.

Open Loop Control

To be able to control the combustion engine during cold starts and lambda-malfunctioning, an open loop control was introduced. The open loop is determined by two parameters: ambient air conditions, and engine oil temperature. The ambient air is used as an input to adjust for air density during different conditions. The difference in air density is laid in as a compensation 1-D map, and is purely based on ideal gas-theory, as can be seen in figure (17), where the compensation values for different air temperatures is introduced:

Air Temp C -40 to 125	Fuel Comp % -90 to 500
-10	9
-5	8
0	6
10	3
15	2
20	0
25	-2
30	-3
35	-4
40	-6
50	-9
60	-12
70	-15
80	-18
90	-21
100	-24
110	-27
115	-28
116	-29
120	-30

Figure 17 Ambient air temperature based compensation for open loop control

To enhance the open loop control, one more compensation table is introduced, which enables the operator to map the engine during different engine temperatures, one 1-D compensation map for engine oil temperature is introduced. This makes it possible to adjust for cold start and warm up conditions. Further, an open loop 1-D map for injector opening time is introduced in the Simulink model for mapping of the open loop, with engine speed as input. It should be clear for the reader that this is where the main open loop mapping is done, the two aforementioned tables is strictly for compensation, to adjust for different conditions.

Both oil temperature and air temperature are Bosch NTC-circuit sensors, which is widely used in passenger cars.

Exhaust Temperature Input

Exhaust temperature is used as a mapping input for the operator. This is strictly an operator input to see what the exhaust temperature is during adjustment of fuel and ignition. Through this, it is possible for the operator to adjust fuel and timing to reduce the risk of hardware failure during operation. The exhaust temperature sensor is a K-type thermocouple with a serial amplifier. The exhaust temperature sensor is mounted 20 mm away from the exhaust port and is of the 3 mm type.

This input is one possibility for future work, as it gives one more control parameter to be introduced.

Idle Control Output

One idle input will be introduced in the ECU. This will control a solenoid of some sort to enable idle conditions for the ICE. In its first iteration, it will be an open loop solenoid. This is one area for future improvements, as closed loop idle is a big advantage for stable idle conditions.

Starting and Loading the Engine

Instruments

A 2.2 kW ABB induction motor is used to start and load the engine. The electric motor is regulated by a variable frequency drive which has 144 ohms of additional braking resistance to dump the energy generated by the ICE. The resistor bank has a capacity to dissipate 2.4 kW of energy which is sufficient for the engine in consideration. A Fluke scopemeter was used to measure the potential across the braking resistors.

Figure 18 Resistor banks, VFD controller and Fluke scopemeter used for power measurements

Starting the engine

To start the engine, the electric motor is used to crank the ICE to a speed of 1500 rpm which corresponds to a motor speed of 750 rpm (there is a gear reduction of 2 between the electric motor and the engine crank due to the sizes of the two sprockets). Since the electric motor is controlled by a variable frequency drive (VFD), a correlation between the speed of the motor and the input frequency was established which formed the basis for regulating the speed of the engine (the chart has been appended to this report). Corresponding to the crank speed, the frequency is around 13 Hz, at which the VFD is set and the engine motored.

A point to note when starting the engine using the VFD is that the braking resistors need to be disconnected so that the engine doesn't get loaded while trying to start, see figure 19. This is applicable if the engine is required to run in idle mode wherein it would stall if loaded. However, the engine will continue to operate so long as the motor is running but again this is not a recommended operating point for the engine. When the motor reaches the crank speed, the ignition is turned on and the engine firing commences. At times the engine required the throttle to be pulled to assist in the cranking. The moment the engine speed exceeds that of the motor controlled by the VFD, an error message would be displayed (when braking resistors are not connected) and supply to the motor would be cut. Under this condition, the engine will run at the no load condition and the electric motor does not have any power input from the VFD.

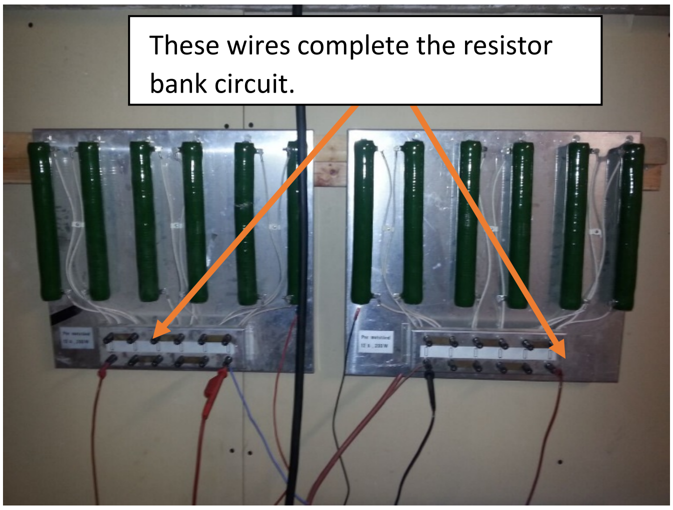

Figure 19 Resistor bank circuit

Loading the Engine

To load the engine, the braking resistor bank must be connected to the VFD to dissipate the generated energy. The principle behind loading the engine is that the VFD controls the electric motor speed and tends to reduce the engine speed from the no load condition (maximum speed at the given throttle position) to a lower value depending on the VFD setting (*Both the electric motor and the ICE run in the same direction, only the regulated speed of the motor would be lower than the engine*).

The electric motor is the dominant of the two and hence the engine speed is always dictated by the VFD of the motor. Hence while loading the ICE, the VFD is first set to run at a speed that is close to the no-load speed of the ICE. The speed of the ICE is then gradually decreased by lowering the frequency of the VFD using the potentiometer which consequently leads to loading the engine.

Taking the Measurements of The ICE Power

The potential is then measured across the ends of the resistor banks which is used to estimate the power generated by the ICE. The relation between the energy dissipated through the resistor banks and the power generated by the ICE is that the VFD routes any power generated by the ICE through the resistor banks and since the ICE is the only source of power, the potential across the resistor banks is a direct indication of the ICE power.

The power calculation is determined from the relation $P = V.I = \frac{V^2}{R}$, where V is the potential across the resistor bank and R is the total resistance of the resistor bank. Engine torque can be determined from the relation $T = \frac{60P}{2 * \pi * \mathrm{N}}$,where T is the engine torque, P is the engine power and N is the engine speed in rpm.

VFD Settings and Operation

The VFD has been pre-set in a ready to use condition. However, in the event a reset is required, the following settings need to be performed.

Brake resistor active setting: $06.00 \rightarrow 0$

Potentiometer frequency control: $02.00 \rightarrow 4$

Show total power: $00.04 \rightarrow 7$

To get familiar with VFD operations refer (12) and (13).

Scopemeter Settings

A Fluke scopemeter was used to measure the voltage across the resistor bank. To visualize the voltage reading, the following settings are required:

- Set Input to DC
- Set measurements to VAC+DC
- Perform correct scaling on voltage

Testing Procedure and Approach

Initial testing was performed to check that all installed test apparatus were functional, for instance the ignition kill switch, logging switch, logging channel connections, voltage readings across load bank and exhaust evacuation from test area.

To start with the testing a run-in cycle was prepared although testing difficulties made it hard to follow this cycle, 2 engines were run-in at part-load and low load conditions for an average of 4 hours. Initial testing was to obtain the engine power, torque and exhaust lambda value as responses. A provision was made for exhaust temperature measurement as well but it was not utilized due to the lack of an amplifier.

The testing process at the start was arduous due to exhaust gas leaks and insufficient suction from the exhaust vent fan which caused the entire test area to smoke up and trigger the CO alarm for most of the time. This was a critical health and safety issue for the ICE group members and personnel at ITRL and was hence attended to with priority. The solution was to provide a direct exhaust pipe connection rather than to relay the exhaust through the evacuation fan. Additionally, seals were mounted on the exhaust piping interfaces that were earlier susceptible to leaks. Following this the exhaust problem was largely solved.

The logging equipment had some connection issues which was resolved in a couple of days after understanding the circuit diagrams. Initial testing had some uncertainty on engine running condition due to non-sustaining run. This was later realized to be because of the constant loading of the engine even when it was set at idle condition which naturally caused it to stall. It is suggested that future teams read through the electrical loading section carefully as although it was not complicated, the intricacies were not explained at the start and hence the understanding was arrived at after reasonable time and effort.

Once the engine run-in was completed, the next task was extracting the base engine performance map. The idea was to use the model based calibration toolbox (MBC) of MATLAB to speed up the process through design of experiments (DoE) and data modeling.

The DoE used was a space-filling design which is a typical experimental design approach for cases where the response behavior is not clear. This was preferred as power-torque curves were not readily available for the GY6 and the manufacturer does not provide this information either.

A 50 point DoE was generated and after filtering physically non-feasible points, 47 test points were required to be tested.

There were numerous practical issues with the test setup which stalled test plans and delayed obtaining results. The carburetor proved to be very erratic in its runs with mixtures too rich or too lean. The carburetors from other engines were fitted to check on the possible defect of the original one but all the carburetors seemed to be performing the same way. Adjustment of the air-fuel ratio screw did not help either. Due to these limitations it was decided to attempt to retrieve the full throttle performance curve of the engine at the very least. While this run was being attempted, the drive chain broke loose and stalled the testing once again.

It was observed that the chain had heated up and the oil lubrication used was ineffective due to oil splash and the inability to retain the oil. It is recommended to have some spare chains and to use grease in place of oil. The chain was found to have mild abrasive wear around some rollers however, due to lack of time it was decided to fix the chain, oil soak it and use it again. There were also some misalignment issues between the engine and load motor which was rectified.

In total 34 test points partially from the DoE setup and from the full throttle attempt was logged. Limited data was now available until 60% throttle and remaining data points at 100% throttle opening.

While this is not conducive for accurate data modeling since it relies on interpolation techniques within the tested data points, to show the capability and have an idea of the application of the tool, a test data based representative map of the engine torque and lambda value was modeled.

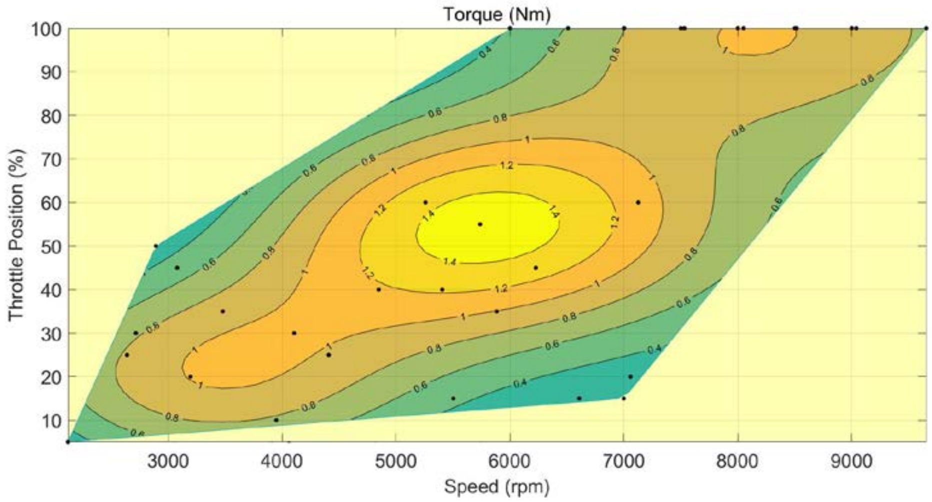

Figure 20 Torque as a function of throttle position and engine speed based on tests

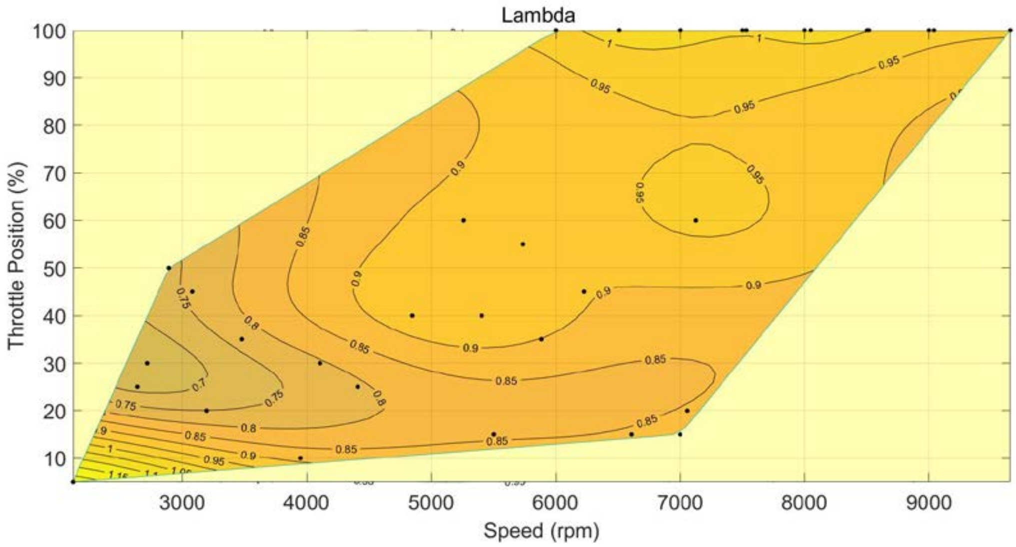

Figure 21 Lambda as a function speed and throttle position

It can be observed from the torque plot that the peak torque and power values are not achieved through the limited testing performed. This is attributed to the erratic carburetor behavior which varies from one carburetor to another and was inconsistent with air-fuel ratio screw adjustments and did not correct with the installation of an air filter. Since the engine ran extremely rich with the air filter, the tests were performed without an air filter.

Summary

The purpose of this project was to have a functional vehicle running on ethanol before the EcoMarathon competition and to optimize it for fuel efficiency. Since a decision was made to change fuel type for this year, last year's results needed to be reevaluated with that in mind. With last year's results and recommendations in mind, the ICE team decided to change the engine to delete the bevel gear and get an engine more suitable to run on Ethanol.

A decision was made to use a scooter engine, GY-6, after some extensive research due to its relatively high compression ratio, simple construction and availability of parts. As this report is written, the car is not fully functional. However, a functional engine test cell has been built which consumed much of the time of the project and tests on the new engine have been conducted. The next step before the competition is to implement a fuel supply system to run the engine on ethanol and make an engine map based on the new fuel and controls.

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Improving the Drive-Train for ELBA

ELBA - Car competing at Shell-Eco Marathon

August 2016

KTH ROYAL INSTITUTE OF TECHNOLOGY

SHELL ECO-MARATHON

MF2020

Improvement of existing Drive-Train on ELBA

Authors:
Daniel Hallberg
Maadhav Padmanabhan
Parsa Broukhiyan

Supervisor:
Mikael Hellgren

August 27, 2016

KTH Industriell teknik och management

SUMMARY

Shell Eco-Marathon is a competition conducted by Shell Corporation. The ELBA car built by KTH Royal Institute of Technology, competed in the Urban-Concept Car category, where ethanol was used as fuel. In this competition each team was given 4 attempts, in each of which there was a time limit of 45 minutes for the car to complete specified number of laps around the track. The team to complete these laps within the given time frame, with the least amount of fuel consumed was declared the winner of the competition.

ELBA is a car that was developed for the aforementioned competition by the students of KTH in the year 2015. Although the car was well made, like any other product,it had a lot of problems. The students from the batch of 2016 were to refine this car. The Shell-Eco Marathon team from KTH has 3 major teams - (1) Mechatronics, (2) Internal Combustion Engine(ICE) and (3) Machine Design. The main objectives of the mechatronics team are to design a system in order to compute an optimum drive cycle and to control elements like the clutch, engine ignition, lights. While the ICE team had to develop an ignition controlled engine that runs on ethanol. Finally, the Machine Design team has to improve the existing drive train and incorporate a better clutch mechanism so as to make the system more efficient.

The clutch mechanism that was being used was inefficient and the parts used were worn out. One of the main reasons for the inefficiency of the clutch in the previous design was that, the actuators were exerting more force than necessary and also this force was being exerted even after the needed part was engaged. So the idea was to have a clutch mechanism that wouldn't need the actuators to exert a force after the necessary parts were engaged. It was decided to retain as many parts as possible from the previous drive train model and come up with a new clutch that could be accommodated into the existing drive-train model.

The new clutch mechanism makes use of balls and springs that are inserted into the hole drilled through the shaft at appropriate positions. A bushing with a grooved profile is made so as to slide axially along the shaft. The grooves were made in order to accommodate the balls that pop out once the clutch is fully engaged or dis-engaged. The spring force pushes the ball against the face of the groove thus locking the clutch in position i.e. not letting the clutch slide axially until the force is exerted by the actuator. Although the clutch mechanism proved to be efficient, the drive train as a whole did not prove to be highly efficient owning to the minor misalignment in shaft and the high amount of friction at the bearing shaft interface.

Keywords : Shell-Eco Marathon, Ethanol, Mechatronics, Machine Design, Internal Combustion Engine, Clutch, Drive-Train

ACKNOWLEDGEMENT

*We take this opportunity to thank **Mr.Mikael Hellgren** who gave us a chance to be a part of building ELBA and also guided us through the process. We would like to thank **KTH Royal Insitute of Technology** for extending the necessary funds to participate in Shell-Eco Marathon at London and to obtain the necessary accessories to build the car. We shall remain indebted to **Thomas Östberg** for machining the parts needed for the drive train on time. We would also like to thank **Per Risberg** for his whim and wit even at tense moments at the paddock. Last but not the least, we would like to thank the members of the **Mechatronics** and the **IC engines** team, whose assistance at crucial times helped us deliver our goals.*

TEAM MACHINE DESIGN

Contents

Chapter 1

INTRODUCTION

This report discusses at length the efforts made to improve the existing drive-train by the Machine Design team. This section in particular gives a brief description of the basic functioning of the old drive-train and it's disadvantages. In the subsequent sections the new drive train design will be dealt with in detail.

1.1 Previous Drive-Train

In this section a brief description of the layout of the old drive train and it's working is discussed.

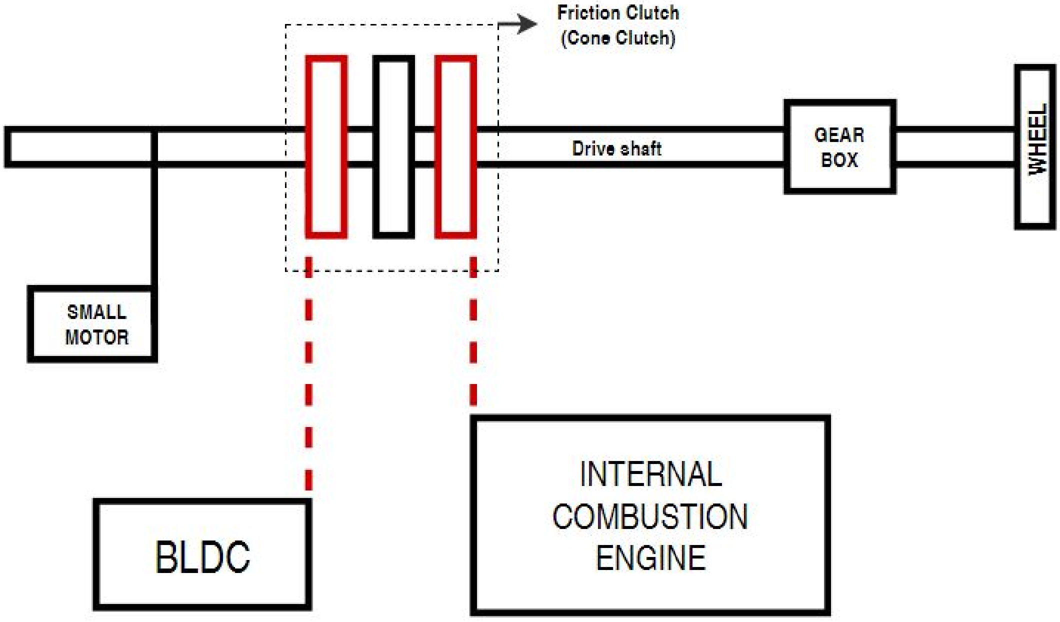


Figure 1.1: Layout of the old-drive train (A rough schematic)

Figure 1.1 shows a simple schematic representation of the layout of the old drive train. The components shown in red indicate that they are not always connected to the drive shaft. They are engaged and disengaged at will. However, the other components are always connected. The small motor is always connected to the drive-shaft. While the power from the BLDC (large electric motor) and Internal Combustion Engine(ICE) is drawn only when the respective clutches are engaged/mated with the center disc that is always rotating (indicated by the black rectangle in between the two red rectangles in **figure** 1.1) with the drive shaft.

1.1.1 Working

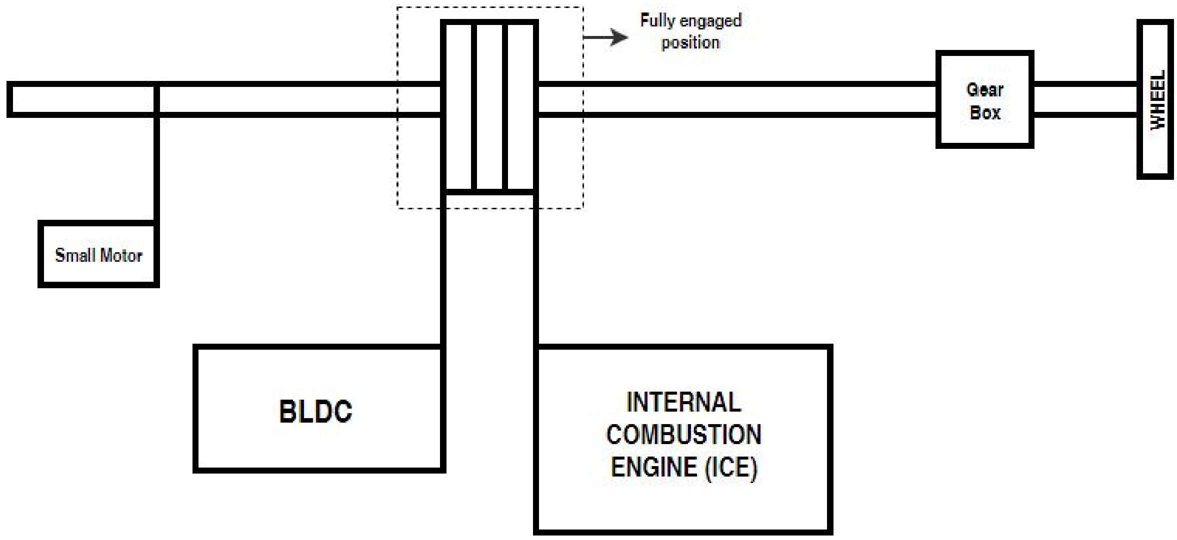
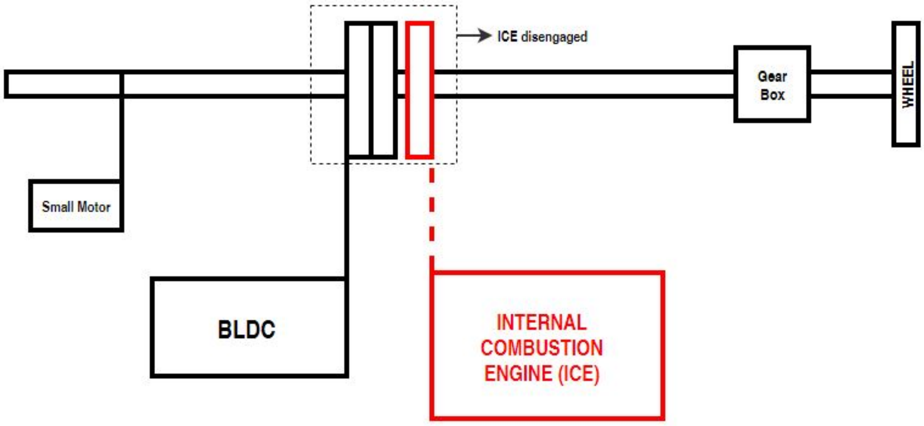


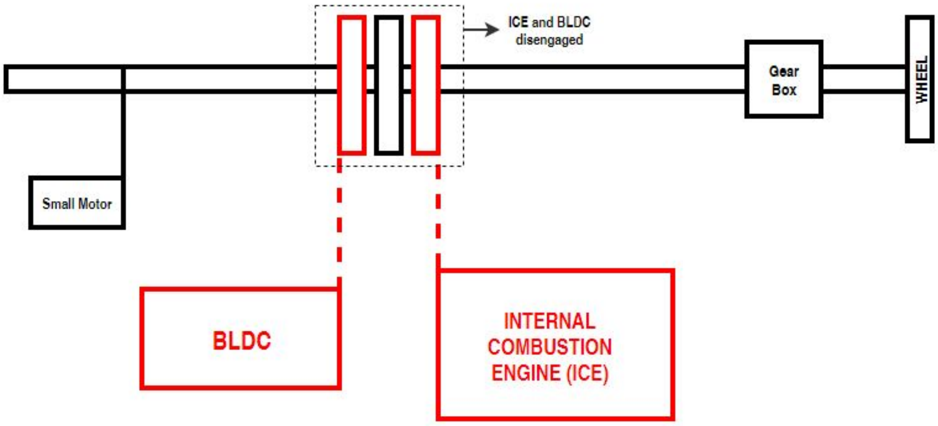
Figure 1.2: Start position of the drive (A rough schematic)

Figure 1.2 shows the schematic of the drive train when the car begins to move. Here, the BLDC is in fully charged condition, and all the components are engaged. So, the power from the BLDC is used to fire the ICE. This power from the ICE is used to propel the car forward. Now, the BLDC has utilized some power to start the ICE and this has to be replenished. So, the power is no longer supplied to BLDC, and the car is propelled by the ICE. During this the power from the ICE is also used to charge the BLDC. Once the BLDC is charged to 48 volts (fully charged state) the ICE is disengaged. After this there are two possible scenarios:

- SCENARIO 1 - when the car has to accelerate
- SCENARIO 2 - when acceleration is not needed



(a) SCENARIO 1 (A rough schematic)



(b) SCENARIO 2 (A rough schematic)

Figure 1.3: Drive Train layout for Scenario with acceleration and without acceleration

Scenario 1 - Acceleration

Figure 1.3a shows the acceleration scenario in the drive train setup. In this case both the small motor and the BLDC are used to run the car, the BLDC in addition to the small motor provides the means to accelerate. Once the power from the motors are used up, then the ICE is again engaged and the motors are recharged.

Scenario 2 - No acceleration needed

In this scenario, as seen in **Figure** 1.3b both the BLDC and the ICE are disengaged and the power from the small motor is enough to drive the car at a constant speed. Once the charge drains from the small motor, the ICE and the BLDC are engaged again and the power from the ICE is used to charge the motors.

It can be seen that, whenever the ICE is running the BLDC is engaged as well, however the converse need not be true. So, the point of using the ICE is mostly to charge the

BLDC whenever it runs out of charge. The usage of ICE is limited to just charging the motors because the main objective of the competition is to cover larger distances with less consumption of fuel.

1.2 Disadvantages of the old drive train

The existing drive train did not perform to it's potential. The reasons for that were analyzed by making observations of the functioning drive train and by taking it apart to see if all the components were intact. The following observations were made:

- The clutch mechanism was not functioning. The reason being, excessive force applied by the actuators. Due to this excessive force, the clutch plate stuck very hard to the center plate and could not be deactuated easily. Also, the force being applied on the bearings, to actuate the clutch, caused some friction losses on the bearing elements. So, it was necessary to come up with a new clutch mechanism where force would be required to just move the clutch plates towards the center plate, but not to perpetually hold them against the center plate.i.e there must be other means of locking the clutch plates in position.
- The small motor was always connected to the shaft. Due to this, when driving down a slope the car went on slower speeds than it would have without the small motor. So, there had to be a means to disengaging the small electric motor from the drive train.
- Most of the parts like bearings were worn out due to continuous use during the race.
- The center plate of the clutch was worn out and had to be re-made
- There was misalignment in the shaft due to improper mounting.

Based on the above observations, certain solutions were discussed and implemented. These shall be discussed in the subsequent sections

Chapter 2

NEW DRIVE TRAIN

This chapter elucidates the clutch design solution that has been implemented in the final working model of the car. It must be noted that the layout of the previous drive train was deemed reliable and a decision was made to use the same layout. But, it was decided to improve the efficiency of the existing arrangement by re-manufacturing the worn out components and coming up with a new clutch mechanism.

2.1 Description of new clutch solution

When engaging the ICE or the BLDC, the power flow in the previous clutch mechanism went from the actuator through the rotating ball bearings and into the conical clutch. When an axial force was applied on a rotating ball bearing, friction losses occurred. Therefore, a solution that made use of a spring loaded ball to lock the clutch in the engaged position (to avoid the friction force in the bearings, when the clutch is engaged) was used. **Figure** 2.1 is an illustration of how the power flow was in the old clutch mechanism. It

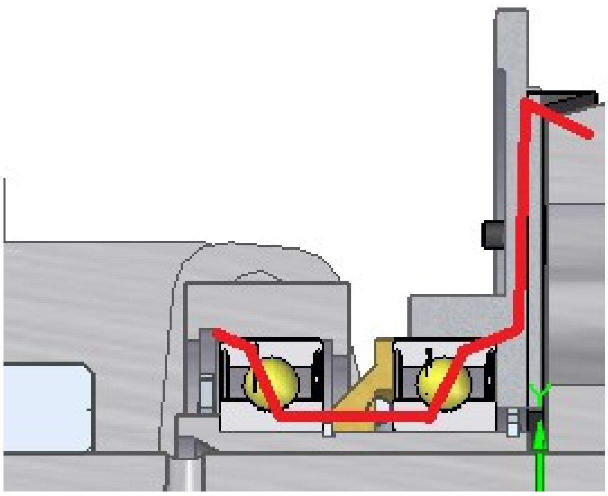


Figure 2.1: Power flow in the old clutch mechanism (red line indicates power flow)

can be seen that the power flows through both the bearings in the fully engaged position.

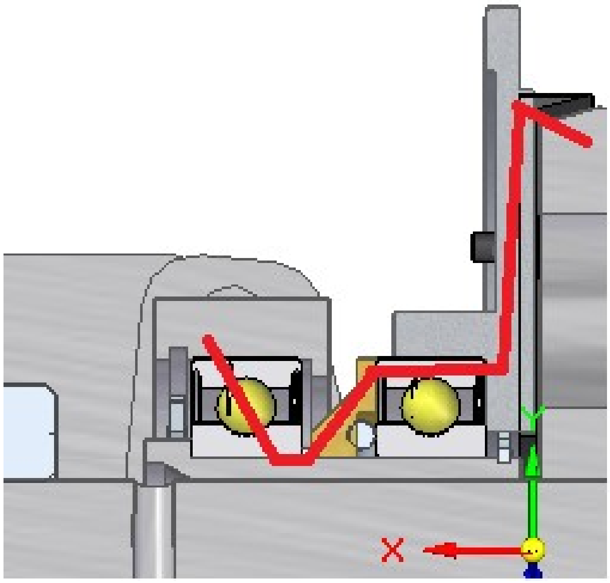


Figure 2.2: Power flow in the new clutch mechanism (red line indicates power flow)

Figure 2.2 illustrates the force flow in the new clutch solution. It can be seen that the power flows through one rolling element only (during the engagement phase).

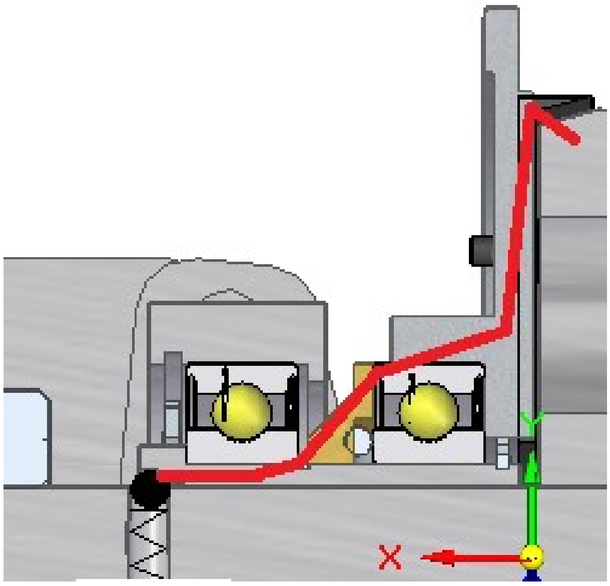


Figure 2.3: Power flow in the new clutch mechanism (red line indicates power flow)

Figure 2.3 illustrates how the spring and ball arrangement in the shaft ensures that no force is transmitted through the balls of the bearing.
This was the concept that was finalized. The next step was to make calculations so as to decide the wedge angle for the spring and ball locking mechanism.

2.2 Calculation

The calculations were made to compute the wedge angle needed. These calculations were not done with very high precision. However, care was taken to accommodate all the operating conditions with some simplifications that would not affect the result largely.

According to [1], as seen in **Figure** 2.4 with the reaction force at the wedge (N_1) due to the spring (P) and ball acting as a function of the wedge angle (α), the force N_2 on the ball can be calculated using **equation** 2.1. This force N_2 is nothing but the force with which the clutch is engaged.

$$N_2 = P * \frac{sin\alpha}{cos\alpha - \mu * (1 + sin\alpha)} \tag{2.1}$$

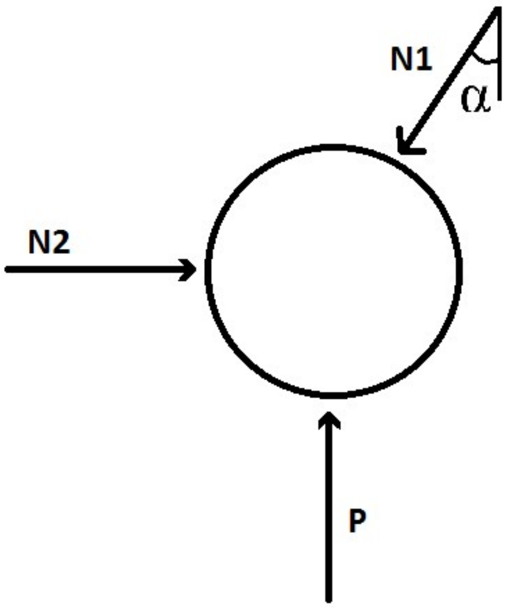
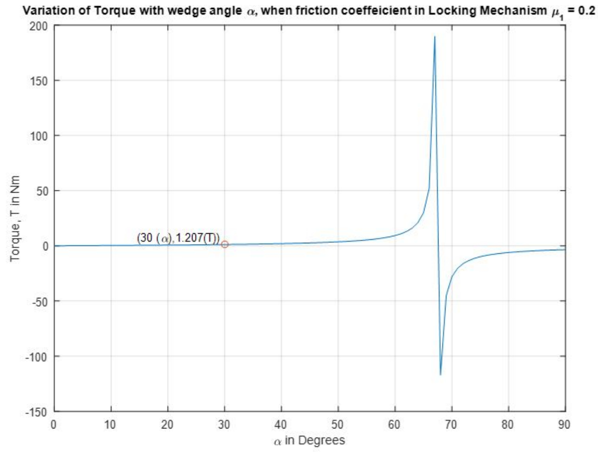


Figure 2.4: Free body diagram of the ball in the locking mechanism

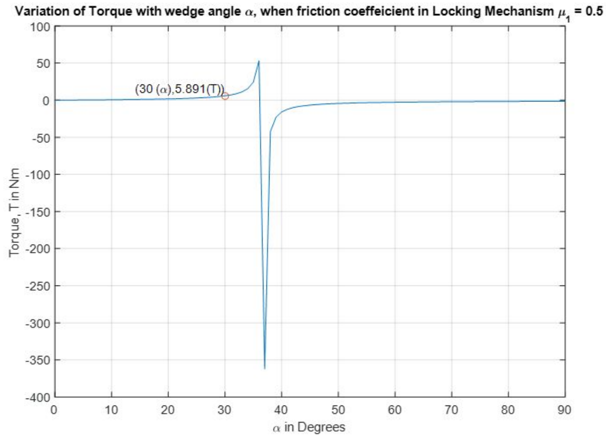
The amount of torque to be transmitted was estimated to be 3-4Nm. This estimate of torque was given by the ICE team. According to [2] the torque to be transmitted by the clutch can be estimated by **equation** 2.2

$$T = \frac{\mu R_m N_2}{sin\beta + \mu cos\beta} \tag{2.2}$$

- $\alpha = 0 - 90°$, tested angles on the locking mechanism
- $\mu_1 = 0.2, 0.5$; friction coefficient of the locking mechanism (Steel-Steel)
- $\mu_2 = 0.6$, friction coefficient of the conical clutch
- $R_m = 0.0955m$, the mean radius of the conical clutch
- $\beta = 15°$, angle of the conical clutch.
- $P = 20N$, minimum force from the spring according to the data sheet given by the supplier



(a) Variation of transmitted torque with wedge angle. ($\mu_1 = 0.2$)



(b) Variation of transmitted torque with wedge angle. ($\mu_1 = 0.5$)

Figure 2.5: Variation of transmitted torque as a function of wedge angle and coefficient of friction of the locking mechanism

In **Figure** 2.5a where the coefficient of friction of the locking mechanism is 0.2, the variation of torque with the wedge angle can be observed. It can be seen that it would be advantageous to have a wedge angle (α) of 60° as the torque transmitted is higher at this value of α and is closer to the given torque requirement. However, when the coefficient of friction of the locking mechanism is higher i.e $\mu_1 = 0.5$ the case is different.

As seen in **Figure** 2.5b, for a higher coefficient of friction of the locking mechanism, the torque transmitted is nearly zero at larger wedge angles (α) i.e. for $\alpha > 40°$. Also, for $30° < \alpha < 40°$ the locking mechanism appears to go on to a self-locking mode. This means that a high force would be necessary to separate the clutch. This made it necessary to make a trade off in deciding the wedge angle. It was decided to have a wedge angle (α) of 30°. Although the torque transmitted initially will be low, eventually with the increase in friction of the locking mechanism the torque transmitted will be higher and shall reach the required level.

NOTE: The MATLAB code for one of the cases is attached in the appendix. The actual and clearer plots of the code are also available in the appendix.

2.3 Manufacturing

The bearings, springs, balls and sprockets were bought from companies, while the other parts were made at the machine shop at KTH with the help of **Thomas Östberg**. The parts that were made in the machine shop were :

- the shaft
- the conical center plate
- the clutch plates
- keys

The bearings needed for the shafts were bought from **SKF** and the planetary gear from the previous setup was used as such. Once the parts were obtained, they were all assembled and manually tested several times. Due to time constraints an integrated testing was not carried out until the race at London.

NOTE : The drawings for all the parts have been attached in the appendix.

Chapter 3

PROBLEMS AND CONCLUSIONS

The drive train was completely assembled and fit into the car a week before the race at London. Once the car arrived at the paddock in London, the drive train team did not have much to do with the drive train itself. Various systems were fixed and the engine was made to fire before the technical inspection. On the race day, **KTH Royal Institute of Technology**, in spite of completing the technical inspection did not finish the race. The car could run only one lap successfully after which the actuators failed to disengage the clutch.

While preparing for the race, the drive train team encountered some problems. These shall be outlined in this section.

3.1 Problems

- The first and foremost problem was encountered during the assembly of the drive train. Once assembled, it was seen that the drive train was pretty heavy and that it wobbled when rotated. The reason for wobbling was unclear initially, but later was attributed to improper balancing during mounting of all the parts. The weight of the drive train can be reduced either by using lighter materials or by reducing the number of bearings (there are currently 5 bearings on the shaft).

- Once the clutch was tested at the integrating stage, it worked fine for the first few runs. But after continuous usage the clutch plates stuck very hard to the center plate and had to be plied open using a crow bar. This problem was thought to be because of the excessive force exerted by the actuators i.e. the actuators exerted more force than necessary on the clutch plates, thus making the clutch plate stick to the center plate with increased adhesive friction (as it is a steel-steel contact).

- The center plate of the clutch moved a minute amount from it's original position after repeated cycles of operation. This is a major issue as it could potentially damage the spring-ball locking mechanism. A better way has to be found to lock the center plate axially to it's original position.

3.2 Conclusion

With the above mentioned problems and suggestions taken into consideration a better drive train can be produced. Also, the force estimates were not given as input to design the shaft. So, the previous inputs were taken and the same shaft was redone. However, it would be better to have the force output from the engine and the motors. With those estimates a shaft can be conventionally designed.

One of the most valuable lessons learnt from this year's race is to always carry out all the testing before going to the paddock. Especially the integrated testing. Sometimes systems might function well independently, but when combined with other systems might not function well. This was a major set-back for team ELBA. Nevertheless, the same car can be modified and made race-ready, for it has cleared the technical inspection.

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[2] Rober L Mott. *Machine Elements in Mechanical Design*, chapter 22, page 855. Prentice Hall , Pearson Education South Asia Pte Ltd, 2006.