Final Report

A report on the subjects covered in the Eco Cars advanced course

Authors:

Helen Ghattas

Tobias Gustafsson

Jimmy karls

Victor Malmgren

Simon Nelson Landén

Milivoj Persson

Rouyu Zhang

Supervisor:

Mohammad Khodabakhshian Khansari

May 25, 2015

Advanced Course in Mechatronics

KTH School of Industrial Engineering and Management

The Royal Institute of Technology

Stockholm

Abstract

This project is part of the advanced course in mechatronics (MF2058) at the Royal Institute of Technology, Stockholm. This course extends to the end of 2015, where a control strategy for minimizing fuel consumption for KTH Eco Cars hybrid is to be developed. The purpose of this report is to present a current state of the art for hybrid electric vehicles and present as well as a design review of the electrical system and powertrain built.

Contents

1 Introduction

Hybrid vehicle techniques have been extensively studied in recent research papers, mostly due to their potential to improve fuel economy, driveability and reduce emissions in future vehicles. Hybrid electric vehicles can be designed to have a dual-power-source nature, which leads to the development of different control strategies that support the investigation of the potential power output and fuel consumption in hybrid vehicles. In this paper, we look into different control strategies suitable for a hybrid electric car and explore the possibilities of fuel reduction. The control system is made for the KTH Eco cars, where the test car is Elba. There are many methods to reduce fuel consumption such as cooling the engine system, energy conversions, energy brake losses, battery charge efficiency etc. The concept introduced in this report is to build the powertrain and control system using model-based design in MATLAB. This allows for a design procedure where different features can be modeled, simulated, tested and verified. The quick development process with model-based programming allows for development of different control strategies and enables the usage of dynamic programming in order to minimize fuel consumption. This template can be exploited by next generation of students for future development and research.

2 Scope

In this paper different control strategies, model-based design, and different HEV architectures are studied. It addresses a way to document a project using model-driven engineering to enable a smoother way to change the control system, powertrain architecture and the electronics involved. The report does not include a control for the internal combustion engine or the design of the drivetrain.

3 Background and Problem description

The work conducted in this report is done on one of KTH's Eco cars, Elba, where the drive- and powertrain is redesigned. The deadline for this is the 19th of May, as there the Elba is scheduled to compete in Shell Eco marathon in Rotterdam. In other words, each of the different parts of the vehicle is a project assigned to different student groups, where our responsibility extends to the powertrain excluding the internal combustion engine as it is assigned to a different group. As the details of each subsystem are not known when we have started our work in February, the optimization and analysis will be conducted in phase 2 of the project when the competition for Shell Eco marathon is done.

Developing fuel-efficient vehicles are of great importance in recent days. Accomplishing as low fuel consumption as possible contributes to maintaining natural resources; the vehicles become more attractive economically to consumers as well as lower emissions are produced. But the requirements concerning comfort and performance are increasing; the balance between the two driving forces allow for alternative ways to reduce the fuel consumption [1]. One approach concerns the structure of the chassis to reduce losses from aerodynamic drag, rolling resistance, braking losses.The second course of action is to enhance and make the powertrain more fuel efficient, either by optimising and developing of different components, such as batteries, ultracapacitors, engine, drive shaft, etc. This leads to a strategy of actively combining the existing powertrain's components into a configuration that achieves better efficiency. The other course of action is to optimize the control strategy of the powertrain. This is a higher level than the component level; developing a model-based template in MATLAB is a possible solution to present the overall system configuration and through a control strategy could produce a synergy that should make the final product better than just the addition of the individual components themselves. Our goal is to build a model based template where the parameters mentioned above can be changed and modeled in order to test different structures that could lead to reduce fuel consumption.

4 Requirements

In order to be able to participate in the competition, Shell Eco-marathon, there are quite a few rules to follow. This implies a certain constrain on the design choices and therefore implicitly regulate the developed system. Course responsible and supervisors together with the customer to which we are delivering the system to, add on requirements onto the finished result as well. All of these requirements have been identified and addressed during the project and an extensive Excel sheet have been made, where the requirements have been added and managed. The Excel requirements sheet have been formatted to support the desired and necessary metadata acquired along with their desired requirement. This sheet is developed for two main reasons: The first one is to clarify each requirement, at the same time archiving it so that it is accessible to all team members. The second reason is the ability to link the sheet of requirements to the main Simulink project, where the simulation blocks can be traceable to specific requirement. MATLAB has a built-in method for traceability, which allows for an easy way to verify each requirement.

5 State of the art

5.1 Hybrid electric vehicle powertrain configurations

There are clear motivations for developing hybrid cars. It leads to better fuel economy, lesser emissions, increased comfort and safety, and flexible drivability. For example, the fuel consumption is reduced when the size of the combustion engine is reduced due to added electrical energy and also due to regenerating braking energy.

A typical drivetrain of a hybrid electric vehicle (HEV) involves internal combustion engine (ICE), generator, battery packs, rectifier, capacitors, converters and electric motors [14]. Originally there were two main types of drivetrain configurations for a hybrid vehicle; Series hybrid electric vehicles (SHEV) and Parallel hybrid electric vehicles (PHEV). In later years, two additional types of hybrid vehicles have been introduced. The first one is the series-parallel hybrid (SPHEV), which is a combination of the two original types, and the other one is the complex hybrid (CHEV). The four types of HEVs are developed due to different requirements, depending on the application of the vehicle the configuration of the hyrid car changes, whereas the parallel hybrid is the most commonly produced of the four. The four classifications are shown in the following figure 1.

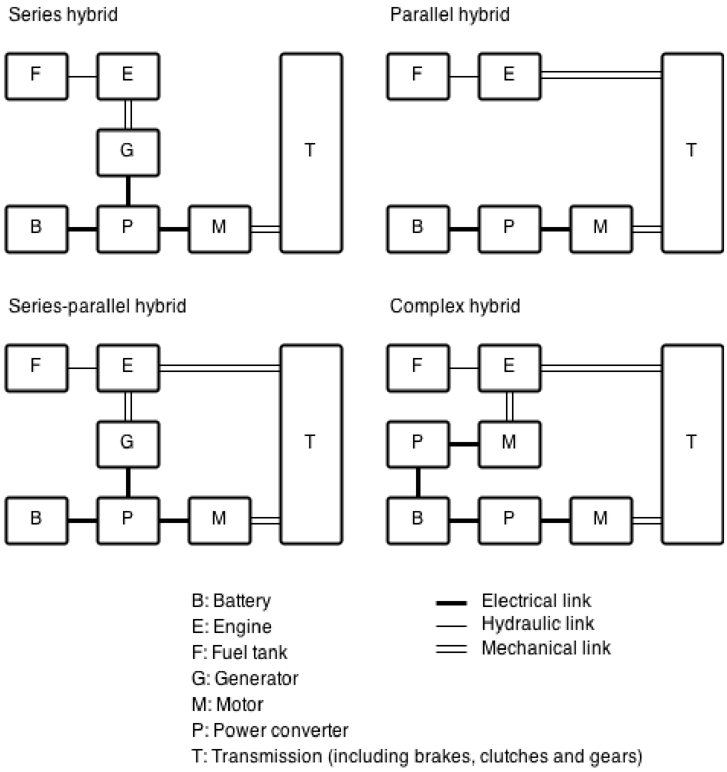


Figure 1: Classifications of hybrid electric vehicles. Figure influenced by [14]

5.1.1 Series hybrid

In a series hybrid electric vehicle (SHEV) , there is no connection between the ICE and the wheels, the combustion engine is connected to the generator and its only role is to supply the batteries with power. The ICE always operates at its maximum efficiency point and if the power generated is higher than the power necessary to propel the car, the remaining power is used to charge the batteries [14].

The most significant benefit of the series hybrid is in its simplicity and that the position of the ICE and the generator is more free due to the absence of clutches in the mechanical system. The disadvantages of the series hybrid (compared to a parallel hybrid) is the need for three propulsion devices (engine, generator and electric motor) and that these devices need to be dimensioned for maximum sustained power in case the vehicle is needed for long climbs. The series hybrid vehicle has to have a large enough electrical energy source in cases where the vehicle needs to be used in longer distances.

5.1.2 Parallel hybrid

In parallel hybrid electric vehicles (PHEV) the transmission is powered by both the mechanical- and the electrical power-output. The reason for the popularity of the PHEV lays in its ability of using the power split between the thermal and electrical energy. The structure comes in different configurations depending on the control strategy used.

In a PHEV, the ICE is almost always on, where it is designed to operate as close as possible to the maximum efficiency point. When more output power than what the ICE can supply at it's maximum efficiency point is needed for the demanded operation, the electric motor is turned on in order to supply the extra power needed to drive the transmission accordingly. When less output power is needed at the transmission, the extra power is then used to charge the battery packs that supply the electric motor. This is done through regenerative braking and does in turn ensure that the ICE can work at its maximum efficiency point at all times.

5.1.3 Series-parallel hybrid

The series-parallel hybrid is a combination of the series hybrid and the parallel hybrid as its name suggests. It has the positive features of both hybrids and the only downside is the complexity and cost of creating such a system [15]. Although complex, with new technologies in control strategies, modeling and manufacturing, it's easier to implement this system and many cars have implemented the design already.

5.1.4 Complex hybrid

As it's name suggest, this system is a complex configuration of the powertrain which cannot be classified into the above three kinds.The complex hybrid is similar to the series-parallel hybrid, but an important difference is that the generator used in the series-parallel hybrid can act both as a generator and as a motor in the complex hybrid.This allows a power flow in many different directions, for example using all three motors to propell the car. Controlling this system can be very complex due to the power split and the manay different drive modes a complex hybrid car includes [15].

5.2 Development and documentation strategies

5.2.1 Model-Based Design

In recent years, more companies started to concentrate on Model-Based Design (MBD) in the software domain and have seen clear benefits of it. The results include a faster time-to-market, and shorter and cheaper development processes. This leads to a verification phase early in the project [7]. Some of the benefits of using MBD are inlisted as follows [8]:

- Using a common design environment across among project teams
- Linking designs directly to requirements
- Integrating testing with design to continuously identify and correct errors
- Refining algorithms through multi-domain simulation
- Automatically generating embedded software code and synthesizable HDL code
- Developing and reusing test suites
- Automatically generating documentation
- Reusing designs to deploy systems across multiple processors and hardware targets

According to two papers written by [9] and [4], research was conducted to investigate what the major benefits of the MBD is in real projects. Both found that MBD made it easier to communicate between employees with different background and knowledge. The MDB makes the code graphical which makes it easier for people without a software background to be engaged in problem solving or the development process. Another positive side benefit of making the code more graphical is that it is easier for the whole team to get an overview of the system as a whole.

A clear benefit is that the testing can be frontloaded, in other words some of the testing can be performed much earlier in the development process. Late and therefore costly changes can be avoided and the changes can be made in concurrence with the requirements before anything has been integrated, implemented or produced. This frontloading is made possible through MiL, SiL, PiL, and HiL tests.

Another, maybe not so explicit benefit is that the code can be generated automatically, which enables the shift of manpower from handwriting the code to other areas. The generated code also assures that no errors are made, handwriting code is error prone as it is writen by humans. The MDB also takes care of the technical aspect of making code run well on the hardware like transforming float-point variables to a fixed-point equivalent. If a part of the system is supposed to be implemented on a microcontroller, those models are converted to implementation models.

One of the major benefits of using MBD is the possibility of reusing the models. The reuse makes it possible to have a base to build upon and only change some parts of the system [4]. This approach enables the developers to document the development in the models and the code is generated in an automated way, which makes it consistent and with little risk of forgetting or writting in an incomprehensible way by the programmer. This will make the company independent of a handful of employees who know the product while no one else does. Another benefit of MBD is the abstraction layer that is placed on top of the hardware, which makes the model valid even if the hardware changes. The MDB also enables a team to work in parallel to a greater extent and the software can be tested and developed even though the hardware is not done or maybe not even decided.

One important fact to consider is that MBD by itself will not help, what is needed is a MBD culture and an understanding of how it works and how it should be implemented. It was shown that there was a correlation between the companies that did not understand MBD and an increase in cost after implementing MBD. The reason for an increase of cost is that the tools needed for MBD are expensive and that it costs money to educate the employees. The new infrastructure is needed in order to convert the hand-written code/system to a model-based system. The companies that understood MBD made significant financial savings. The researches found that it is important to have a system that is easy to follow through a guideline,for example,to get the most out of MBD. In [9] it was found after comparing the companies that three factors influence costs, time, and quality the most:

1. High Modeling degree on function model level and a high degree of generated code
2. Intensive test activities on function model level (MiL-tests, model reviews and RCP)
3. High know-how of the employees in MBSD and in SW-engineering

The companies that incorporated this made the biggest savings.

The drawback of MDB is that the whole development depends on the accuracy of the model. If the model is not derived properly, everything that is developed from it will be unusable as the model does not correspond to the reality in which the system will be used.

MDB is easy to integrate with a popular development process called the V-model. Here the different stages of the development process are defined from idea and concept all the way to delivery.

It seems like MBD is a very good fit for our project, as this project is a continuous project with new team members every year. This means that there will be handovers and reuse of the basic functions. What will be changed is the algorithmic part of the model, the driver blocks will be the same or easily replaced. It can be compared to a facelift; If a different drive train will be used it will be easy to move the blocks around, add blocks, or remove blocks. The new configuration can then be tested in a MiL test to see if it improves the performance of or not. A concern that was pointed out in the research was that people need to be trained to be able to use the tools. But as the students the following years will have a similar background and have experience of the tools we use, it should not be problematic. In [8] a list of ten rules to follow for best practices is found. ??

5.3 Model Architecture

5.3.1 GT-power

Where DT-Power is a engine simulation software, where it is possible to design and develop the engines. GT-POWER contains advanced set of models for engine performance analysis, providing the features required needed for analyzing a number of engine configurations and performance characteristics of different system set ups. GT-POWER uses the nonlinear Navier-Strokes equations for the motion of viscous fluid substances to obtain good accuracy in predicting the behavior of complex engine related phenomena. At its core, the GT-POWER solver is based on the 1D solution of the fully unsteady, nonlinear Navier-Stokes equations. Beyond this core lies the state of the art of GT-poer's thermodynamic and phenomenological model solvers. These solvers are used to capture the effects of combustion, heat transfer, evaporation, in-cylinder motion and turbulence, and engine and tailpipe out emissions, etc. This combination of solvers provides the users with model accuracy for required torque, Brake specific fuel consumption (bsfc), airflow, etc., as well as present detailed strategies for injection system and emission specie concentrations anywhere in the system.[12]. This seems as a powerful tool to use when analyzing a internal combustion engine but is not suitable for an entire system simulation as our car has to be a multi-domain model.

GT-Power simulations have been studied and used in many researches as a tool for simulating engines. The tools have proved to be a strong one that is capable of simulating an entire internal combustion engine, especially the complicated parts as gas exchange system and the turbocharger [16]. In other reports such as Sellnau and Rask variable valves were investigated and their effect on engine performance were evaluated. Therefore, the GT-Power simulations are good tool to assess forexhaust gas recirculation (EGR) systems and decide their strengths and weaknesses. In other reports, the GT-power is used in order to perform optimizations strategies for a gasoline engine intake system. All in all, the GT-power is a good tool for simulation and validation of engines [16].

5.3.2 AMESim

AMESIN is a software that supports multi-domain mechatronic systems. LMS Amesim libraries are written in C language and also support Modelica, which is an object-oriented, declarative, multi-domain modeling language for component-oriented modeling of complex systems, e.g., systems containing mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented sub components. Modelica was developed by the French company Imagine SA (now part of LMS International), Dymola from the Swedish company Dynasim AB, and other bigger companies, which makes it compatible with many platforms.

The LMS platform for multi-physics modeling, LMS Amesim, is based on a single, integrated platform, providing a set of multi-domain libraries that are packaged and authored into multi-domain models to simulate vehicle systems.[13]. The models created can be tuned to deliver real-time capabilities with regard to offline simulation. Also, these models are developed to handle fast and efficient calculations, managing transient nature of driver usage scenarios, including warm-up cycles, start/stop, etc.

MDS has lead to a paradigm shift where mechanics, electronics and software in a new design can simultaneously be optimized as an integrated mechatronics system. This empowers the handover to the next revolution in engineering and encourages innovation.

LMS Imagine.Lab Amesim supports many desirable features such as platform facilities; where the user can see the simulations with the help of graphical user interface and statechart design. LMS tools support co-simulations with other CPUs and parallel processing as well, which helps with different levels of testing. Another benefit of using LMS is the wide range of solvers used for ODEs: LSODA, DASSL, DASKR, Fixed-step solvers, etc.[17]

5.3.3 Mathworks

Creating models in various physical domains, such as electrical, mechanical, and hydraulic is hard to integrate, even though it is developed in MDS. There are many conclusive reasons; the testing is hard to do in early stages and the integration between subsystems in later stages are prone to failure as different languages has been used up until this point. According to statistics of real cases, the development of subsystems with different languages cause more than 55 percent of the overall errors[11]. Mathworks has as a goal for developing model-based design tools to achieve error detection in the specification level instead of in the testing level. Simscape is developed to support multi-domain in different environmental models, where signal processes are supported and different control algorithms are implemented and tested in real-time simulations. The rapid prototyping process includes as well code generation, which minimizes the errors coupled with hand-written code. The model-based programming is based on designing drivers that match the structure of the system being developed. It provides fundamental building blocks from different domains that can be assembled into models of physical components, such as electric motors, hydraulic valves, etc. Model based design allows for two main benefits which are collaboration across disciplines and collaboration across development disciplines.

This will be useful for us in the competition, as different parameters will have to be changed or modified according to the logged data from each lap. This calls for an interaction between modeling/simulation and code generation/adaption. Simulink can be used for HIL-testing as code can be generated and verified. This supports the V-model in developing new systems in an ordered way, where traceability is available between the code and the documentation.

To reach the final software, a standard platform needs to be created. This platform divers is the code is generated for prototyping or for production. For a prototype, the whole system is simulated and some parameters are not yest known, but the code for production has to be optimized for certain drivers that already exist and where good interface is necessary to standardize the production and control algorithms. Simscape is essential for engineering work and helps toward an optimized design for both developing software and physical system together. Simscape is used to optimize system-level performance and to create plant models for control design.[11] The models you create support your entire development process, including hardware-in-the-loop simulations. Simscape constructs the differential algebraic equations (DAEs) that resembles the characteristics of the system. The benefits of using Simscape is that the differential equations are integrated with the rest of the Simulink model, and the DAEs are solved directly.This allows for avoidance of algebraic loops as the variables in the physical domains are solved simultaneously.

5.3.4 Comparison between the different simulation tools

The difference between the different simulation tools can be summed up as follows: The code used in GT-power is one dimensional, meaning that it only uses one direction and time. In order to get three-dimensional simulations GT-power must be coupled to different solvers. Some of these solvers are external full 3D computational fluid dynamics solvers, e.g. openFOAM, StarCCM+, and Ansys CFX. This is a huge back draw as the hybrid electrical vehicles contains electrical and mechanical systems that need other fixed or variable-step solvers. Industries and car manufacturers use AMESim and all the other simulation tools. Therefore, the license for them would be hard to get and the time to learn these softwares would take time. On the other hand, AMESim is supported of the Modelica modeling language, and the Modelica Standard Library (MSL) with dedicated tools is included: modelica editor, modelica import assistant, modelica compiler, modelica assembly. This makes this LMS Amesim an open platform, which is supported by many platforms. However, MATLAB is a software all team members are acquainted with. There is nearly no difference between LMS Amesim and Mathworks, so the decision to use MATLAB was easily made. The tools mentioned here are only a fraction of the simulation tools available; the reason for picking three simulation tools was chosen in order to get a comparison. In our case, the whole system is still under development and the drivers can be chosen according to requirements, but for future work on Elba a standard platform is needed. This platform has to be flexible for future changes and support existing or new drivers.This calls for a platform that can combine all the different physical models into one platform that allows for interactions between the different subgroups.This is the reason why we looked into Autonomie.

5.3.5 Autonomie as a tool for model building and management

Different companies use several tools as mentioned in the previous sections to develop detailed plant model. The objective of Autonomie is not to provide a language to develop detailed models, but to support the model assembly developed and to use these models from the first stages of design until the simulation stages in order to analyse the models[10]. The support that Autonomie provides is through a plug-and-play architecture that is in line with ideal use of modeling and simulation for math-based automotive control system design. The standard format for model-based programming is to create building blocks, which are assembled at run time into a simulation model of a vehicle, system, subsystem, or component to simulate. On the other hand, in Autonomie all parts of the graphical user interface (GUI) are designed to be flexible to support architectures, systems, components, and processes not yet envisioned [10]. This software allows individual test to the models, and the model can be expanded and changed as requirements and technical knowledge changes. This flexibility include models, controller code, processes, drive cycles, and post-processing equations. Autonomie has a build-in library as a part of the software package that includes useful and tested models and processes in order to support a full range of simulation and analysis tasks. The reason why Autonomie is such a strong tool is that it can configure and mange a database to facilitate the storage, and maintenance of all required files, models, the model's supporting files, test data, and the reports. This comes in handy when a company has many teams working in parallel with developing and simulating different configurations or parts in the system. The results becomes that each group ends up with its own vehicle model that differs from the other subgroups. None of the subgroups can share or reuse its models because they all use different naming conventions, model organizations, numbers of ports, and other conventions. This is noticed in our work with Elba, where the integration with other groups was not easy, due to different development processes and not sharing the same software. Moreover, trying to integrate the different models together in such cases is on the one hand time consuming, on the other hand duplicating other teams work is prone to errors. For example, the control system used for the engine is developed by a subgroup that perhaps have its own engine plant models, which isn't identical to the model plant used by the engine plant developers. The back draw with Autonomie is that the model is math-based, which class for good knowledge of every subsystem and what the effect, loss, torque and other parameters are. The system that we are developing is not yet verified with the real car and therefore it is not suitable to use Autonmoie in the first phase of this project. However, after analysing the data from each lap a verification of the model can be made and can be used to build a math-based model. Mathworks runs as well on all operative system, which makes it a good candidate as it is not limited to some platforms in future work.

5.3.6 Documentation

In some multi-project based organisation, one of the difficulties the organisation faces is how to improve the concept of "lessons learnt", the knowledge obtained from the different projects needs to be codified and shared in order to obtain institutional knowledge but as there are no incentive to motivate knowledge sharing, it remains a as local and unexploited knowledge[5]. In every project there is a need for balancing between exploitation of new solutions and existing knowledge, in cases such as ours where previous projects documentation are incomprehensible there will exist no balance and the focus will fall in requiring the same experience and knowledge again, which could have be easily acquired had the documentations been any good. This often leads to a minimized time for creation and developing new ideas as /textitreinventing the wheel has taken up a significant time from the project. The reasons for lack of documentation is correlated to the human beings nature and individual motivation; documentation is not considered as an interesting activity and therefore tend to be neglected [5]. In project based firms, there exist three learning process: experience processes, knowledge processes and knowledge codification [6]. Where experience knowledge is local and is obtained by accumulated experience, the knowledge articulation is symbolic and earned by reflecting over the obtained knowledge. Lastly, the knowledge codification is institutional knowledge that is written and adapted; in this stage the possibility of codifying manuals and procedures exists. But this process has to have a framework in order to maintain a reliable work structure. Making a framework is time consuming and has to be easy enough so that each team member can easily document obtained knowledge. Such solutions are being used in different firms, as they are facing quite similar problems. Some alternatives that can be used for modeling and simulation is Autonomie or Simulink, that can be used as a platform for good documentation and hand over. The reason for choosing MathWorks over others is primary because we have license for it and we can at the same time simulate, collaborate, generate code, verify and document. Another benefit is that a report document is produced automatically from the code generated making the interface and traceability available.

Another problem that projects suffer from is the discontinuity between parallel projects; different projects are developed separately and integrated in last stage of the development process. A beneficial feature is the model-based innovation in Simulink that allows collaboration between different disciplines that causes collaboration across the whole development process. This will enable to deliver whole control architecture in one simulink project where all relevant drivers are included and the report can be generated from the project using a relative link, this allows for a good traceability between the documentation and the code generated. This will hopefully ease the hand over and allow the next team to quickly and in a comprehensible way take over the project.

The state of documenting in software development is to design document that include API specifications, manual pages, and code comments. The major drawback with this kind of documentation process is that whenever the requirements or specification later change the design choices have to be reconsidered and the manuals have to be rewritten and updated.This procedure is time consuming and the main devotion for a developer is to design, implement, debugg and maintain the code. This calls for software that extracts documentation from the source code maintaining a structured relationship between the comments and the programming constructs the API writers document. To make an comprehensible documentation the following should be included:

- API Reference Guides
- Programmers' Guides
- Developer Manuals
- Administration Manuals
- Installation Guides

5.4 Control strategies

Currently, there are many methods used to develop a supervisory control strategy. In this section of the report, some of the more common control strategies are presented. Control strategies can be classed into causal (real-time/online) and non-causal (offline). Furthermore, the controllers could also be classified into heuristic, optimal and sub-optimal [20]. The goal of the controller is to reduce fuel consumption under different constraints. Constraints being different system operating ranges such as battery or super capacitor SOC, efficiency maps of the different motors and engine, along with other more specific constraints. In addition, other goals can also be incorporated; such as minimize emissions, increase performance etc.

5.4.1 Global optimal control strategy

Optimal control strategy is an offline strategy and is developed with dynamic programming in order to determine a global optimal energy management system (EMS) and a priori knowledge of the driving cycle is needed. Global optimal control is as straightforward as DP and is capable of handling nonlinear equations through Bellman's equation. However, the optimal control strategy cannot be used in real-time because DP is an offline control strategy, meaning that it needs the future drive cycle for computation. Another problem with the use of DP is that it has long computational time even though it has shorter computational time compared to the traditional brute force enumeration [18]. If the drivetrain and powertrain are identified, then DP could be used to in order to create the whole model math-based. Depending on the complexity of the system the model can be described numerically or analytically. The next paragraph will explain what DP is and how it is used in developing control strategies.

The potential in fuel economy is still an ongoing research field where different approaches exploit existing control strategies based on engineering intuition [2] or explore new control strategies using different or combined control methods. For example, dynamic programming (DP) is an effective technique to find globally optimal use of multiple energy sources over a predefined drive cycle. The main advantage is that it can handle constraints and nonlinearity of problems, while obtaining a globally optimal solution for the whole system [3]. The DP technique is based on Bellman's Principle of optimality, which states that the optimal policy can be obtained if the first stage sub problem solution involves only the last stage; the solution expands thereafter gradually to sub problems involving the last two stages, last three stages and so on until the entire problem is solved.

Dynamic programming as any other optimization problem has to have an objective; reducing fuel consumption, energy management or optimizing control strategies etc. The information in DP is gathered concerning the current time and makes a decision called the state. The control strategy that is used for the driving cycle will affect the state and the next states as well. Therefore the results from PD can be used to design the control strategy that satisfies the essential objective. Moreover, Bellman's equation for optimization problem can be used in discrete time and in a recursive manner, providing dependencies between earlier time periods. Finally, the optimal decision will be the one that achieves the best possible value of the objective. In our case, the fuel consumption minimization is a goal which is explicitly coupled to longer traveling distances.

Using a simple control strategy in the car is not optimal for us, since it is component-based and not system-based. And in cases where the knowledge about the degree of improvement is unknown, DP is recommended to be used as an analysis and design tool. Due to the nonlinear characteristics of the hybrid powertrain, it is not possible to solve DP analytically. Instead, DP has to be solved numerically by some approximations. A standard way is to use quantization and interpolation [3]. Nowadays, the time-line for vehicle design is decreasing, while simultaneously the number of possible powertrain configurations is increasing. Previously, the evaluation of a powertrain configuration was achieved by doing *hardware* evaluations, that is, assembling and evaluating many possible system configurations. As the speed of production is increasing, it is not possible to make all design decision on the basis of hardware alone as it is time consuming and expensive. There is a tendency for design decisions to be made upon the basis of mathematical models and analysis[3]. In the next phase of our project, we will explore how the use of DP could assist in making powertrain design decisions on the basis of component models. We will explore the use of Dynamic Programming to make model-based design decisions. Our goal is to make Elba more autonomous in the next phase, as it is very dependent of the driver in the first phase. DP could help us to determine which control strategy is suitable for Elba. Supervisory control actions for Elba needs to include the power split between the engine and motor in order to maintain the super capacitor SOC-sustaining constraint. The reason behind using DP is that the control strategy can be designed accordingly to the optimal driving cycle of the car in the competition. With already decided components and from the data logged from different test runs, a numerical and optimal solution can be calculated. Every node from point A to B has to be passed but the energy source will be different at each point, with DP a decision can be made at each point. This decision is explicitly based on the basic relationship of the torques:

the torque provided by the internal combustion engine and the electrical motors in accordance to the super capacitor's SOC constrain. One reason for the popularity behind using DP is that it allows flexibility in defining an object function, for example reduced emissions, sustaining the SOC. This leads to a production of different optimal solution [18]. However, a control strategy based on DP is theoretically optimal, which means that it is the best solution under a specified vehicle drive cycle and a certain HEV architecture. Even though control strategies provided from DP would be ruled to be insufficient, DP can be used as benchmark to judge the performance of different control strategies.

5.4.2 Sub-optimal control strategy

In the case were no priori knowledge of the drive cycle is available, global optimal control cannot be applied. Instead, other methods may be used such as sub-optimal control strategies. For sub-optimal control strategy, there are two methods to use: Heuristic control strategy and equivalent consumption minimisation strategy.

Heuristic control strategy is often called Rule-Based (RB) [19]. This control strategy determine when to switch on or off the engine and determines the amount of electric charging or discharging power applied by the electric motor. To achieve this behavior the control strategy uses *if-then* logic. The drawback with this control strategy is that it is dependent on the application, meaning that if the drivetrain topology, the vehicle dynamics, or the drive cycle changes, the control strategy is not optimal anymore. This is due to DP, which is used in optimizing the power-split ratio between the engine and the second energy source (electrical). Therefore, optimal control strategy is often preferred; these control strategies are developed based on optimal control theory and can be applied to different driving cycles. A good note to consider is that heuristic control methods could be used when reasonably accurate physical models of the vehicle are not available, which is the case with Elba concerning the clutch system.

The second method includes equivalent consumption minimisation strategy (ECMS); which Guzzella and Sciarretta used to calculate an equivalent fuel flow rate [20]. Their strategy is a well known concept in the research field for HEV control strategies. Through ECMS an instantaneous cost function can be evaluated and fuel consumption can be minimized by selecting a proper value for the torque split control variable.

Sub-optimal control can be used when the knowledge about the driving cycle is not known because it minimizes the cost function at each time instant, as Guzella and Sciarretta presented in their report [20]. The equivalent consumption minimization strategy (EMCS) is a real-time sub-optimal energy management strategy, in which the cost function at one given time includes the fuel energy and electrical energy constrains. This strategy is based upon the assumption of an average efficiency of a battery's discharge/recharge state and the efficiencies of electric motors. DP is only used to find a ratio that could weigh the two different energy sources through a equivalence factor λ. ECMS is a minimizing cost function, which takes into consideration the fuel energy used and the electrical energy used with an equivalence factor $s(t)$, that varies with time, t. The core of ECMS is $s(t)$, and is divided into charging and discharging equivalents[20].

Other optimization techniques and tools exist. One being Pontryagin's minimum principle (PMP). PMP differs from DP in the sense that it is more suitable for on- line adaptions and applications as stated by Chasse and Sciarretta [21].

In parallel hybrid cars, the power is split between the thermal and electrical paths. This feature has positive effects reducing the fuel consumption as the engine is downsized, in addition to regenerated braking energy. However, the control strategy of parallel hybrid cars depend on the power split factor obtained. There are different kinds of powertrain architectures with the common feature that they all share the same set of paths from which power can be drawn from or regenerated to. These paths are:

1. Common path: The overall path of power for the vehicle. This is the necessary power needed to propel the vehicle forward regardless of its source. The control variable used to decide the source is the torque split factor, $u(t)$, that regulates the torque distribution among the parallel paths.
2. Fuel path: Using torque split factor, $u(t)$, the torque and speed output from fuel path can be backward-forward calculated. The available power output from the fuel path is calculated through efficiency and operating point maps resulting in a torque out to the wheel. This torque may differ from that of the desired torque.

3. Electrical path: Same backward-forward calculations performed as with the fuel path, but the SOC from energy storage is the constrain together with a similar motor map as the one used in the Fuel path.

There are many ways to determine the power split factor, the most popular being:

1. The Energy paths from the tank to the battery: The average efficiency of energy transformation is calculated by looking on the efficiency of charging and discharging the battery.
2. The state-of-charge constrain (SOC): This method uses different simulations for different control inputs given a certain drive cycle and also a specific upper and lower SOC. One obvious draw back is that it is limited to a known drive cycle, but in our case this is not considered a problem as we are developing a control system for a specific drive cycle. Anyhow, this is an offline control strategy, which means that the power split ratio λ can not be adapted to the SOC because there will be no feedback as the control is non-casual.
3. Heuristically controlling the SOC: This method adapts the control power flow out of the battery using discrepancy between the reference relative value of the state-of-charge of the battery and the actual energy level in the battery. This is a good method if the drive cycle is not known.

As a result of the dual nature of hybrid cars, sets of driving modes can be achieved. Depending on the overall topology of the drivetrain, the most common drive characteristics can according to Hofman and Steinbuch, [19], and Kessels et al, [22], be described as:

- Motor only. Vehicle propelled using the electric motor drawing power from the electric power bank. In this mode the combustion engine is shut off and ads no drag and no idling losses.
- Brake Energy Recovery mode. Brake energy is transferred into the electrical energy storage. In this mode the combustion engine is off and ads no drag and no idling losses.
- Charging mode. Power output from the combustion engine is higher than the requested

wheel power. This allows for electrical supply charging of the redundant power from the combustion engine.

- Motor-Assisting mode. Combustion engine output power is lesser that the requested power out on the wheels and is therefore aided by the electric motor.
- Engine only mode. All propelling power is drawn from the combustion engine. The electric motor ads no drag, and no idling losses.

Switching in between these modes are done differently for different control structures. For ECMS this is done through the $u(t)$, which results in smooth transient mode switches. Additionally, it is possible to apply learning schemes to change the modes of operation. One presented by Michiel Koot et al [23] has some characteristics of heuristic control, but differs due to its ability to change its operation as it learns the behavior of the vehicle. The control parameter for mode switching is the SOC in Michiel Koot et al [23] control.

5.4.3 RB-ECMS

Hofman and Steinbuch [19] look into how to obtain the highest control for the Energy Management Strategy (EMS). They introduce a control strategy with the combination of rule-based management and the consumption minimization strategies (RB-ECMS). This strategy is a response to the drawbacks of DP, RB and ECMS. The parameters that determine the control strategy is the maximum propulsion power of the secondary power source, which is made into an unique decision variable. Moreover, the control strategy is independent of the type of drivetrain topology[19].

5.4.4 The control strategy's comparison

In this section the relative different control strategies are compared:

Subject	EMS	Rule-Based	ECMS
Real time	no	no	yes
Offline	yes	yes	no
predefined drive cycle	no	no	no
Fuel efficiency	yes	yes	yes
Adaptability to changes	yes	no	yes

5.5 Elba comparison

In the first phase of the project, we are using component level control, such as the speed control of the electrical motors or as the fuel injection of the ICE (handled by the ICE team). The goal for the second phase is to develop a supervisory control strategy using one of the methods mentioned above. The decision will be taken after the competition when the logged data is analysed.

Elba is created to compete in one competition, where the drive path is known in advance. Therefore only a few driving modes are needed.

- Acceleration mode. Torque delivered by traction motor (big electric motor/electric machine) solely since the combustion engine does not have a starter motor and therefore needs the vehicle already in motion to push start it.
- Cruising mode. Torque is delivered by the small electric motor due to its high efficiency at this operating point.
- Recharge mode. Using the big electric motor as generator drawing power from the combustion engine recharges energy into the super capacitor. The small electric motor keeps idling together with the main shaft. Power is during this mode
- Brake regeneration mode. Regenerating energy with the big and small electric motors.

The design procedure for Elba starts by defining a cost function, which is one liter fuel. The cost function has to include a minimization strategy for the fuel consumption over a driving cycle. Then, our design choice has already been made, which is EM dominated. However, depending on the losses we have been struggling with in the last few weeks, our car has been ICE dominated. The losses due to the coupling system are too many for the electric motor to overcome and therefore the ICE has to run a longer time in order to keep the velocity desired and regenerate as well. In the case of an EM dominated hybrid vehicle, The ICE is considerably smaller and will most likely be used to help charge a large battery pack or an ultra capacitor and could be used in order to supply enough power to support vehicle movements during peak demand. On the other hand, an ICE-dominated hybrid vehicle will need a larger ICE combined with a small EM. In this case a small battery pack is required as the vehicle will run most of the time on the power supplied by the ICE. This two configurations will need two different control strategies. This has become an obstacle for us and the best control strategy for Elba is still not finalized.

What we can conclude is that the drive cycle for the Shell Eco marathon is going to be changed in 2016 and that the powertarin including the ICE or/and the drivetrain is probably going to be changed for next year. This means that it is useless to develop an optimal control strategy, what is needed is a control strategy that leads to an efficient consumption of fuel for the track that Elba is going to drive in. This reasoning has lead us to decide to use heuristic control strategy, and we need to identify all the parts of the model. This has been very difficult to do, because the results obtain after each test round were different. For example, the regenerating has given different results each race time due to the variable mechanical losses; therefore the driver had to have an eye on the super capacitor to make sure the voltage didn't reduce too much. What is needed in this kind of systems is a learning control strategy, and this could be done only after a good power- and drivetrain has been built. The integration between these two systems needs to be better so that a good control strategy can be designed, the integration at this stage need a lot of work still. The controlling of the clutch system is an interesting mechatronics challenge that should be included in the control system and optimized. The whole system needs identifying as well in order to decide what kind of control system is needed or otherwise exchange it with an electrical clutch. As it seems right now, the only constrain we actually need is the SOC and the only way to keep the voltage level is through engaging the ICE and use the regenerating braking.

6 Pre-study

In the pre-study, the design choices for the components used in the powertrain and electronics in the prototype Elba is discussed and the reader is given a basis for the design choices and technical constrains.

6.1 Micro-controllers

We chose to use Arduino mega controllers for the first phase of the project as the planning time before the competition is short and the Arduino mega are easy to learn. Moreover, the controller can handle all the things that is required at this stage. For the next part of the project we are thinking of using a controller that has more computational power and could handle more instructions per second. The controller examined for future work is the BeagleBoneBlack.

To implement the control system, good microprocessors with good development environment and development boards are needed. Because the code has to be generated from MATLAB/simulink it is important that the microprocessors are easy to use with the MATLAB embedded coder. Six different options has been evaluated. Arduino, AT90can128, Raspberry pi, Infineon, Beaglebone black and dSPACE with some compatible processor using target link. The Arduino board is easy to use, available and the code generation works out of the box. However, CAN and encoder interface is missing and extra external components are required. AT90can128 is the processors used on the car previous years. Rasberry pi has good computation power but no ADC, can or encoder support. The infineon processor has good interface but it is old and hard to get up and running. Beaglebone black is good over all but more complex and needs a RTOS. The option to use dSPACE and target link to generate code for some of the supported processors has been investigated but support is required from dSPACE and the time is not enough to get this before the competition.

The important factors and a ranking for the different options are summarized in table 6.1. The weight for the factors are: available 8, easy to use 7, code generation 7, computation power 5, interface 6, future safe 5.

Subject	Arduino	AT90can128	Raspberry pi	Infineon	Beaglebone black	dSPACE
Available	10	8	10	8	9	0
Easy to use	10	5	8	4	6	2
Code generation	10	5	8	6	7	8
Comp. power	5	5	10	6	10	8
Interface (pwm, ADC, encoder,can)	5	7	3	10	7	9
Future safe	8	5	8	5	8	9
Wighted sum	315	226	300	249	295	209

6.2 Electrical motors

6.2.1 The big electrical motor

One of the first choices that we took was whether the automobile would be ICE dominated or EM dominated. One of our goals is to build a vehicle that is fuel-efficient and therefore an EM-dominated vehicle was chosen. In typical EM-dominated vehicles, the electric motor, which is the main propulsion system, is slightly bigger than the ICE in terms of output power. But as the ICE is not a part of our scope and a bigger engine from HONDA was chosen due to better efficiency, a bigger EM had to be included to be able handle all of the output power from the ICE in order to charge the super capacitor safely. The ICE is a 4 stroke engine which has a peak efficiency around 3000 rpm and the power that ICE can deliver at this operating point is around 1.1 kw as can be seen in Figure 2.The ICE that is used in ElBa is being optimized as well since it is a project that is being done by students from combustion engine department. The results from this experiment is still unknown and therefore the only requirement we have is that the big electrical motor needs to be able to handle enough power to regenerate as much energy as possible and charge the super capacitor without too much losses. This means that the big electrical motor should have a maximum efficiency point somewhere between 0.9 kw and 1.1 kw at an appropriate rpm considering gear ratios.

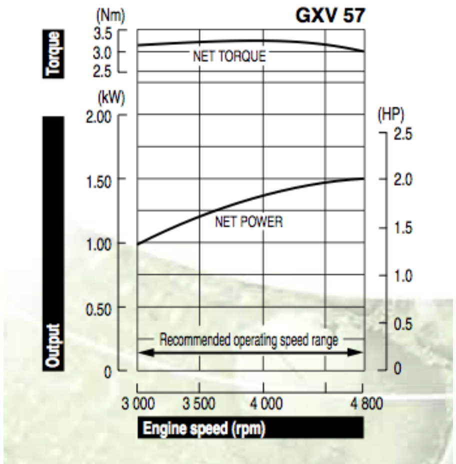


Figure 2: Efficiency curve

There are two motor candidates; the first motor was given to us by inmotion and it fulfills the requirements in terms of nominal power, speed, torque. The critical disadvantage is the size and the weight of the motor that is 7.0 kg as can be seen in the data sheet in appendix A1. The additional weight does not compile to the requirements of being fuel efficient as the extra weight will lead to extra fuel consumption, which is the main problem of the motor. Another disadvantage of this motor is it's high amount of *cogging* due to few motor poles distributed at a large area, this is problematic because it means the motor will need a very sound mounting bracket to withstand vibration and to ensure stability during the whole race that consists of 10 laps. The other alternative is a prototype motor from *Dunkermotoren* which fulfills all of the desired properties in terms of rpm, power and torque. It can be seen in the data sheet in appendix A2 that this motor has a maximum efficiency point within the range that was established previously based on the properties of the ICE. The problem with this motor is that it is a prototype motor since it is not yet commercially sold in the market. We used this motor in the competition, even though the motor arrived the day before we left for the competition. The mountings for the motor was manufactured in advanced as we had the datasheet send to us very early and the tunning of the motor was done dirctly when it arrived.

6.2.2 The small electrical motor

A smaller motor is chosen because ElBa is originally calculated to be driven in constant speed most of the time throughout the race for optimization reasons. The simulations based from the data logged from last year's race showed that the car could be driven with constant velocity more than 90 procent of time. That is why we chose to use the small motor from MAXON and the powertrain model was build so that the small motor was coupled in series. With the small motor from MAXON a velocity of 27 km/h can be maintained. It would be unwise to drive the car with a bigger motor as the efficiency would not be as good at a lower output power. The motor has a maximum efficiency point which is close to it's maximum rated output power which means that the motor should be fully loaded with 200 W in order to give the best efficiency. The design choice was based from the data from last year were the power for 27 km/h was about 150 W. Since we have a bigger drivetrain and more motors this year we estimated that the weight gain and losses in the extra gears and chain would land us around 200 W, which is exactly where we want to be when driving the small motor at maximum efficiency.

6.3 Drivers

6.3.1 The big motor driver

The big motor that is used is a brushless direct current motor. This calls for an inverter that can handle the electronic commutation. The big motor is also going to be used as a traction motor and as a generator, which means that the inverter needs to be able to handle bidirectional flow of power. Through this inverter we are able to use regenerative braking, we are able to deliver power back to the super capacitor when the motor is driven in the second and fourth quadrant. The inverter that has been chosen comes from the company *inmotion*, for more details check the appendix. The inverter is suitable to run at a voltage of 48 V, which is the maximum that the super capacitor is able to deliver. It is able to handle up to 30 A of continuous motor current with a peak of 70A during 2 minutes. The inverter is controlled externally through communication via CANopen and the CAN is galvanically isolated which means that no opto coupler is needed for this device, in order to follow the requirements from Shell Eco marathon; the super capacitor and auxiliary battery should be galvanically isolated from each other. The inverter is able to read the nominal voltage of the supply, which is needed for the simple control strategy that is based on the SOC constrain. The back ECU gets the reading of the voltage through CANopen and then the control system knows when the voltage begins to drop low and knows when to switch on the ICE in order to regenerate back some energy in the super capacitor and then switch it off when the super capacitor has 48 nominal voltage. The inverter is very flexible in terms of feedback modes and control modes which makes it a good candidate for a hybrid system that needs to be flexible in terms of configuration. The inverter also has a rather small physical size which is desired when designing energy-efficient hybrid vehicles for Shell Eco marathon due to the strive for keeping low weight and a slim shaped vehicle body.

6.3.2 The small motor driver

The small motor driver is used for the smaller motor from *MAXON*. The driver also comes from *MAXON* and uses a software developed by *MAXON* for controlling and tuning the driver to a specific motor. The driver is suitable to run on a 48 V supply and it is capable of delivering 5 A continuously with a peak current of 15 A for 20 seconds. The driver is capable of driving a DC motor in all 4 quadrants, which means there is a possibility to regenerate energy with the small motor if it is desired. This gives a flexibility of design as the configuration of the hybrid vehicle can be changed in many ways if a smaller ICE is used.

6.4 The communication protocol

We are using the controller area network that was designed according to a vehicle bus standard. The CAN bus is used for data communication between the Front ECU and Back ECU. However, CANopen is used for the communication between the Back ECU and the big motor inverter *inmotion*. There are two types of microcontrollers used in the car; AT90CAN128 and Arduino mega2560. the AT90CAN128 was already used in the car as the main microcontroller last year, and had a working CAN protocol support. Therefore, it was logical to continue to use the CAN bus in our project as well. However, the Arduino mega2560 can not independently support Can communication, to solve the problem a CAN shield was added to the Arduino in order to support the CAN bus. This was a cheap and functional solution for us as there is a limited budget in the project. Moreover, the CAN bus is galvanically isolated and in that aspect we fulfill an essential requirement for the Shell Eco marathon. A short description on how the CAN bus is used is presented in the paragraph below:

There are six nodes that are directly connected to the CAN bus: the front ECU, the indicator ECU, the driving ECU, the ICE ECU,the big motor inverter and actuator ECU.

ECU and Functions	
ECUs	Functions
Front ECU	1.Read signal form steering wheel, break pedal, indicated switch. 2. Send message to tablet(through blue tooth). 3. Control wiper, horn and front indicator. 4. Send and receive Can message.
Indicator ECU	1.Receive Can message. 2. Control back indicator light and break light.
Big motor inverter	1.Receive Canopen message and driving motor. 2.Read voltage and send it to Driving ECU.
Driving ECU	1.Receive and send Can message. 2. Implement command from Front ECU (velocity, driving mode). 3.Receive Encoder signal. 4. Implement control strategy. 5. Control big motor, small motor ,Actuator and ICE.
Actuator ECU	1.Receive message form Driving ECU. 2.Control Actuator.
ICE ECU	1. Receive message form Driving ECU. 2.Control ICE. 3. Receive Encoder signal.

figure (Figure 3) shows the data communication between different subsystems.

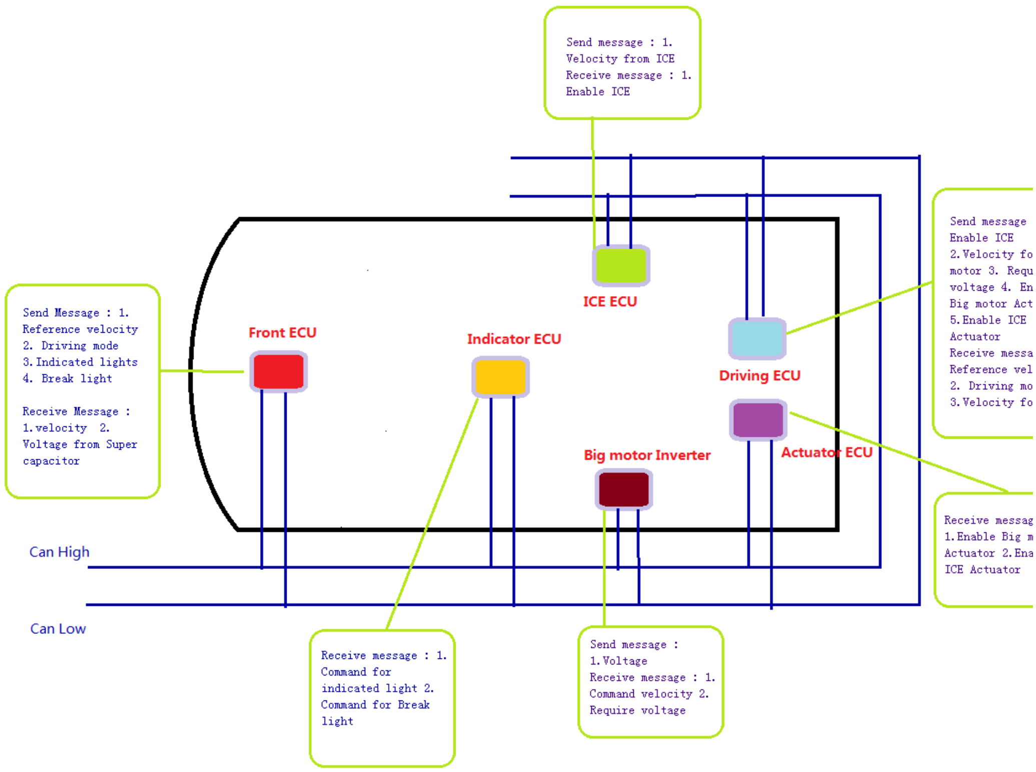


Figure 3: The CAN communication in ELBa

The following shows the communication logic:

ECUs	Send	Receive
Front ECU	1. Reference velocity 2. Driving mode 3. Indicated lights 4. Break light	1. Velocity 2. Voltage from Super capacitor
Driving ECU	1. Enable ICE 2. Velocity for big motor 3. Require voltage 4. Enable Big motor Actuator 5. Enable ICE actuator	1. Reference velocity 2. Driving mode 3. Velocity form encoder
ICE ECU	1. Velocity from ICE	1. Enable ICE
Inverter	1. Voltage	1. Require voltage 2. Command velocity
Indicator ECU	-	1. Command for indicated light 2. Command for break light
Actuator ECU	-	1. Enable big motor actuator 2. Enable ICE actuator

6.5 Driver interface

In order to be able to operate the car properly there must be some kind of instrument that gives the driver the necessary feedback and shows the different internal states of the drivetrain and vehicle overall. For this objective a driver interface has been set up, an andriod app was developed last year for this sole purpose. By using a Android app from the previous Eco Cars teams and modifying it to show additional data the necessary information reaches the driver whilst driving. The Android tablet on which the driver interface app runs on is connected to a front ECU that is placed besides the driver in the driver compartment. The connection is achieved through Bluetooth communication, letting the tablet act as a server-socket and the front ECU as client pushing the information to be displayed to the driver.

The driver interface app handles and manipulates the information received from the front ECU by adding time to the collected data through the means of a timer/counter. It also adds information about the total energy used, the lap-time goal, the desired driving velocity (to achieve lap and race goal time), connectivity information, and regeneration status (if power is drawn from the Super Capacitor or if it is being charged/regenerated into it). In Figure 4 the driver interface is shown as it is displayed to the driver inside the car.

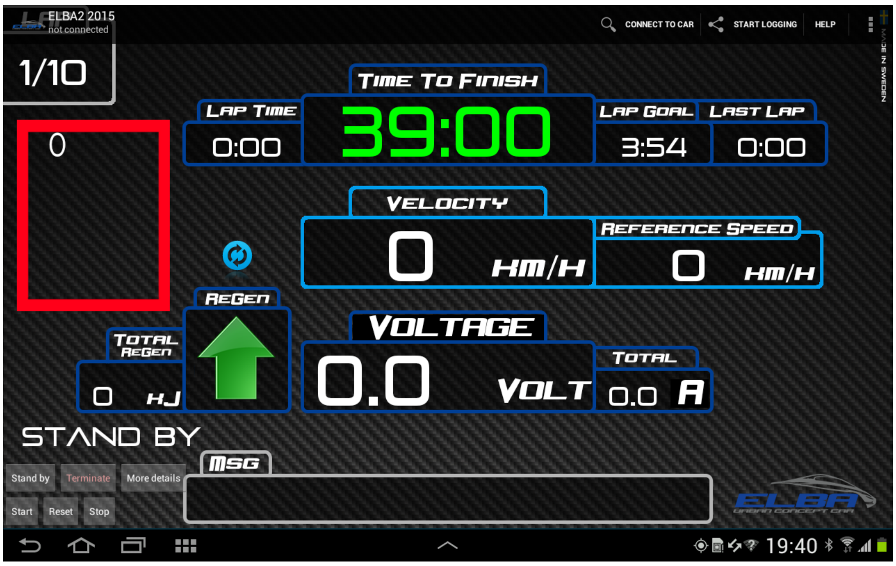


Figure 4: The driver interface in Elba

Another important task that the driver interface performs is the sending of the data to the logging system for ElBa. This is done through the cellular network at regular time intervals, sending all the available information to the log server as will be explained in the following section.

6.6 Log system

The logging is done by sending the data from the driver interface through the cellular network to a server located in the machine design department in KTH. This is a system that has been used by ElBa for the past few years. However, for this year the connections to the server did not work and after some investigation the IT support at the machine design found out that the server has most likely been hacked and was therefore removed. Which means that all the configurations, software and the database were removed for safety reasons. A new server had to be created in order for us to be able to log the driving data; thereafter a very simple back end had to be created on the server in order to log the data from the competition. Using Apache and php, the server stores all data directly to a text on the server. The text file can then be downloaded to a computer using ssh. However to enable live view of the data from the car a database needs to be created and to be used to store the data. Also a more convenient front end should be created, maybe some of the old software can be reused and deployed. For the future the server also needs to have better security to avoid the same problems again.

6.7 MATLAB and SIMULINK

6.7.1 The model plant

Our goal is to build a template in MATLAB that can in some way function as a simulation tool that emphasises on both modeling,simulating and documenting at the same time. A next step is to use Autonomie, which was initiated by General Motors, where a powertrain system is modeled and simulated, which is basically a Matlab/Simulink based software simulator. Autonomie is used to analyze different powertrain systems primarily for fuel efficiency and emission comparisons. It has been used in different researches in industrial and academic applications. The software uses forward looking simulation in which real time signals are used to simulate real conditions. Transient effects such as clutch engagements, torque split can be modeled properly in this software. The template for ElBa will outline the full model of the simulated vehicle of the power- and drivetrain.

6.7.2 Code generation from MATLAB/SIMULINK

In the first phase,that is for the competition, all the code will be generated from Simulink using the Arduino support package. This means that all the scheduling will be handled by Simulink and everything starts and ends in Simulink. There is no need for a real time operation system with boot-loaders, driver and more. However the functionality of the Arduino support package is very limited and many new drivers had to be made for Simulink. The drivers are made of s-function builder blocks or by calling custom C functions from matlab functions. Arduino support package for Arduino mega also gives the possibility to use the external simulation mode. This makes it possible to run simulations from Simulink on the real system. It is very convenient for tuning parameters, identifying and verifying models and to run test without the need of a driver. What can be done in the future is to use a real time operating system and a framework, then generate code that can be deployed in to the framework. However this take a lot of time to do and so far we cannot see any limitations when using Simulink to deploy. ElBA is a prototype and will not be produced or sold to a costumer. So as long as the Simulink approach works for prototyping we cannot motivate that the work put into building a framework will pay off.

6.8 Encoders

The encoder that are used in Elba are from YUMO, which has a resolution of 1024. There is a need for using two encoders in the car; one for obtaining the velocity of the car and the other is used for the injection system for the internal combustion engine. As the Arduino mega is the microcontroller used in the first phase of the project we investigate the need for a decoder in order to reduce the computational load on the arduino. The reason for this was that the motor speed and the encoder pulses-per-revolution (PPR) together led to high computational load. The decodes that were looked into were the hctl-2032 from Avago technologies and the LS7266R1 LSI Computer systems, which are both compatible with the arduino mega. Both decoders have dual axis-quadrature counters, which means that only one decoder is needed. The decoder we used in the first phase is HCTL-2032 due to it's availability in Elfa in quantities. This decoder an external clock is needed as we do not want to use the crystal on the Arduino, we are using an oscillator from Nihon Dempa Kogyo Co, the data sheet and schematics can be seen in appendix. However, for the second phase the beaglebone black has a built-in hardware decoder, which means that the decoders are not needed for the next phase if we use the built-in decoder hardware on the beaglebone black. There is a driver for the built-in hardware module called the enhanced Quadrature-Encoded Pulse (eQEP) that can be used to calculate the position and direction of the encoder.

6.9 Powertrain design choice for Elba

The powertrain of ElBa is similar to a complex hybrid system. The only difference is that the ICE and the electric motors don't have any direct connection between their output shafts, everything is connected through the transmission as seen in Figure 5.

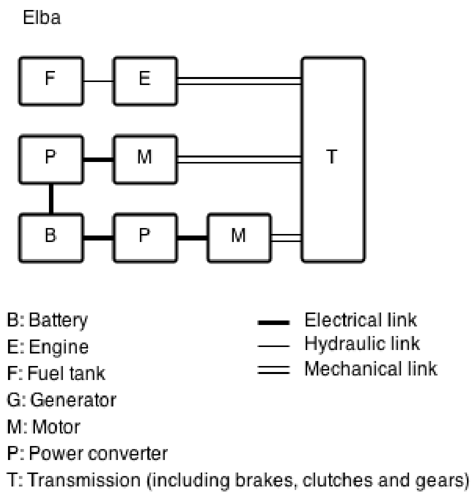


Figure 5: Powertrain of Elba

There are several reasons for choosing a complex configuration for Elba:

- At its maximum efficiency point, the ICE delivers significantly more power than what is needed to keep the vehicle at the desired constant speed.
- The electric motor used for regenerative braking must be able to handle most of the power delivered by the ICE, and does this at its maximum efficiency point.
- The electric motor used to propel the vehicle at the desired constant speed must do this at its maximum efficiency point.
- The electric motor which has its maximum efficiency point at the desired constant speed does not deliver enough power to accelerate the vehicle up to this speed. Therefore the motor used for regenerative braking can be used to accelerate the vehicle and as well as to kickstart the ICE.

The reason for choosing a ICE with higher power is because during early decision-making the group in charge of the ICE came with a proposal to increase the engine size and their reasoning was that it would double the power but still keep the same fuel consumption. From the presented reasons it is clear that two different electric motors, one bigger and one smaller, is necessary since the power needed for braking the ICE and the power needed to keep the vehicle at constant speed is not the same, Moreover, it's not possible to have one motor for both tasks if operation at maximum efficiency point is desired.

The reasons why none of the common powertrain configurations as seen in Figure 1 above is used in ElBa is because:

- A series parallel could work with a more powerful electric motor that could also accelerate the car. But the main reason why a series hybrid was never taken into consideration is because the task given to us from one of our stakeholders was to design parallel hybrid.
- A parallel hybrid would be inefficient because the big electric motor would be inefficient when propelling the car at constant speed. This was the original assignment but after deciding on the more powerful combustion engine, a new more efficient powertrain was

designed to handle the extra power. An efficiency model of the car with all the motors and transmission was created (where most numbers where experienced guesses), the outcome of the model showed that the current configuration was more efficient than a parallel configuration. However, it is important to clarify that the data from the past years are not reliable as the team mentioned in their report that they were skeptical about the results.

- A series-parallel would not work either because the small electric motor, really efficient at constant speed, is not powerful enough to accelerate the car. For this sole reason, we needed a more powerful motor. That's why in the current configuration; the big electric motor is used to propel the car during acceleration and regenerative braking as well.

- A complex hybrid configuration fits the chosen ICE and two electric motors well. The drivetrain team, who is in charge of designing the transmission, presented a design similar to a complex hybrid configuration from the start of the project and suited our configuration after some design choices were improved. The final powertrain in ElBa is closer to a complex configuration than a parallel.

The small electric motor will propel the car for the majority of the time, but its power is too low to accelerate the car or use the regenerative braking to decelerate since it will take too long time and more losses due to friction. The acceleration has to be done by the electric motor with higher power instead. The reason why the ICE can not do this is because it does not have a starter motor, the big electric motor have this function instead. To avoid too many losses during acceleration and regenerative braking, the drivetrain of ElBa is therefore designed so that all three motors and engine are separately connected to the transmission. The big electric motor and the ICE are attached to the mechanical clutches that could be controlled by the linear actuators to engage and disengage. In other words, they could be controlled to connected to the drive shaft whereas the small electric motor is always connected. The main reason for this configuration, in comparison to the complex hybrid is because we want to add the freedom in choosing to accelerate using the big electric motor without having it connected to the ICE. Since the ICE does not start until the car have reached a certain speed, this means the electric motor would have idling losses during early acceleration if the car had a complex hybrid configuration. The ICE experie*cogging* when it is not running which means the losses would be huge. Therefore, we decided to separate the ICE from the big electric motor, but this does not come without a drawback. The power transmission between the ICE and the electrical motor is through the clutch system, which means the losses will be higher and the regenerated energy is lesser than our calculations. This has led to changes in the control strategy where the ICE had to be driven under a longer time under each drive cycle in order to have enough energy in the super capacitor.

7 Critical function prototype

In this section, we will explain how the electronic system works and how the control strategy was developed. We will suggest as well improvements to the next phase and describe the critical functions that we will attend to. A business model is shortly described as it contains motivation to why our concept is important and how is could be applicable in future cars. Figure 6 shows an overview of the whole subsystems in ElBa:

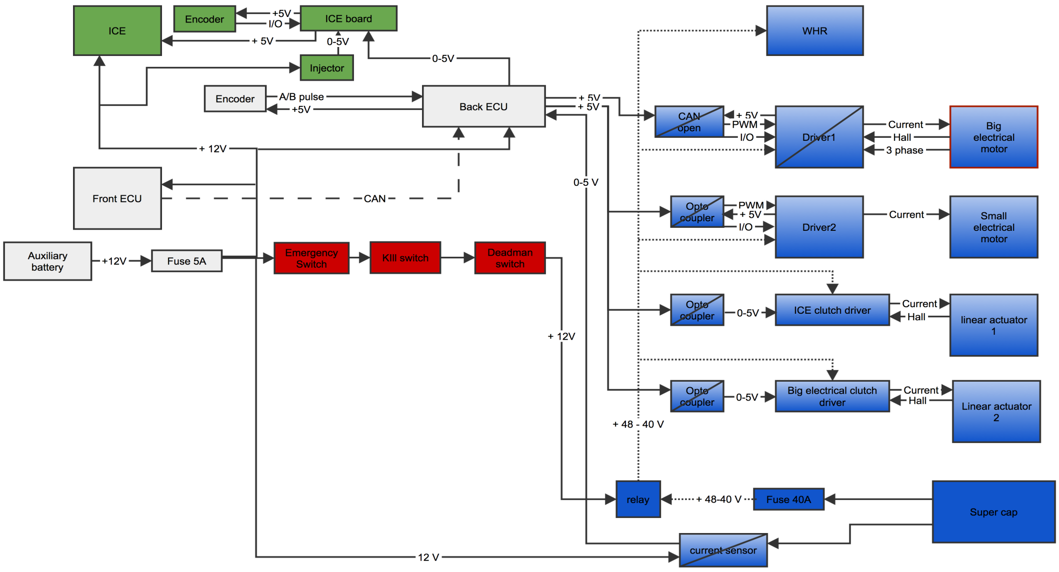


Figure 6: Elba's system overview

7.1 The electrical system in the prototype

The electrical system is divided into three parts, the front ECU, the back ECU and the the propulsion system as can be seen in figure 7 .

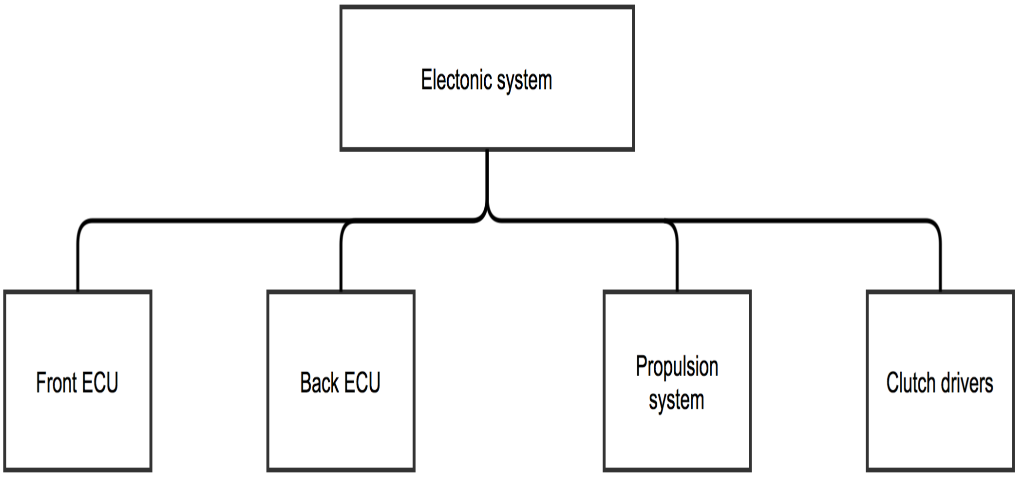


Figure 7: The electronic system overview

7.1.1 Front ECU

We used the same front ECU and code that was made by a mechatronics team in 2013. This ECU is using a development board with at90can128 controller and all code was handwritten in Atmel Studio. The task for the front ECU is to read the input signals from the driver through all the dashboard buttons. Thereafter, this information is sent over the CAN bus to the other ECU:s. The information to the dashboard is also read by the front ECU and displayed on the tablet via the bluetooth module.Only small changes has been made in the front ECU in the form of changing and adding some I/O pins.

7.1.2 Back ECU

The back ECU reads all the input signals from the driver and the sensors such as the encoder. It contains the main control system as well and sends commands to the motors and the ICE. There are three circuit boards in the back ECU; the Arduino mega 2560, the at90can128 development board and the decoder circuit that includes a counter for the encoder signals. The at90can development board is only used to control the indicators and the break light. The code for the indicators and the break lights was reused from year 2013. All the control of the powertrain is made by us,and programmed on the Arduino board through Simulink using the main.slx model in Eco cars control system project. A detailed explanation for the main Simulink block is added to the appendix 10.6. The reason for this is to show how the documentation was held through the project and in this wy the knowledge obtained can be easily shared through team members,see the appendix for more information.

7.1.3 Control system of Elba 2015

The control system runs from a Simulink model, the Simulink template generates all the code and the Simulink model can be used in external mode to see all parameters live in Simulink. Changes are easy to do in the Simulink model and a simple plant model is also provided to do tests without the need of the real system. Overrun detection is used and turns on a led if overrun of any task occurs. To simplify the use and give better structure for different files a simulink project is made and driver blocks and model blocks are included in simulink library browser when the project is open. More information of the simulink model is in appendix 10.6.

7.2 Clutch drivers

7.2.1 Electronics

The clutches are controlled by the driver through the control strategy. This is done by sending some control signals via the opto-couplers to an Arduino Mega 2560. Since there are two actuators, two H-bridges are needed. The engaging and disengaging is through properly controlling the current. Therefore a current sensor is used as the relation between current and force is known. However, the force demanded to engage the actuators was initially specified to 1200 N so actuators with this capacity were bought. After a redesign of the clutch the force needed were decreased to such a small amount that the difference between the current needed to move the actuators without load to engaged was so small that a better result was achieved with timer control instead.

The actuators are rated for 24 volts but the super capacitor has 48 volts. The H-bridges can take up to 70 volts so an initial plan was to limit the PWM so the maximum output voltage would be 24 volts. But when this was tested the H-bridges broke down. A suspicion is that the time constant of the motor is too low so the voltage spikes during switching become too great for the H-bridge to handle. As this is a crucial part of the system, a solution for this was to connect the super capacitor to a Traco voltage regulator that has an input of 18-75 volts and outputs 12 V and a maximum current of 1.3 A. One downside for this is that the lower voltage decreases the velocity of the actuator, but as the timing of the actuation is not crucial this was not a problem. Another downside is that it is less efficient as the Traco has an efficiency of about 90 percent. However, neither this were a problem as the actuator runs for a short period of time. An additional benefit for using the Traco is that the supply voltage is always constant. The power to the Arduino and the logic of the H-bridge is supplied from the super capacitor via another Traco voltage regulator, which outputs 5 V from 18-75 volts. The reason for running the Arduino on a separate Traco is that this ensures continuous voltage to the Arduino so it does not reset, which it will if the 12 V traco is overloaded and shuts off. The H-bridges runs on a slow decay mode as the with fast decay mode interfered with the current sensor as it created a lot of noise on the output signal from the current sensor. They are also configured to have a current limit as a security measurement. So even though the software fails in some way, it cannot break the clutch. For future work, we need to implement over-voltage protection so that the motors can run straight from the super capacitor. Moreover, some additional inductance should be put in series with the actuators in order to increase the time constant. Bu thte most useful one is to swap the actuators for smaller ones with lesser weight and lesser torque as they will be easier to control. Also, bigger amps/newton resolution is needed and will result in a better controller.

7.2.2 Software

The control input signal is either zero or one and are send to each actuator. A low signal means that the driver wants the actuator to be engaged and a high signal means that the driver wants it to be retracted. The whole clutch control logic consists of eleven blocks, five input blocks, six output blocks, and a Stateflow block. The five input blocks are; current sensor input, control action block for the two actuators, and position readings for the two actuators. The Stateflow block transforms the driver into a state machine, a state machine approach makes it easier to follow the logic as it visualize it and because the clutches can only be in fixed states; Actuating, actuated, retracting, retracted. Due to the limited current that the Traco can provide, only one actuator can be active at any point. The low load on the Arduino allows for a high sampling frequency, and the high sampling frequency combined with the structure of the program allows for a minimal use of interrupts. Avoiding interrupts is desired as during testing, a program with too many interrupts crashed when running in external mode in Simulink. The only interrupt used is for the hall sensors in the actuators and they are programmed to fire on one fourth of the possible amount. The code for the position and hall sensor readings is called via a Matlab Function block which use Simulink embedded coder to call the specific functions. The blocks built in the Arduino support package do the reading of the digital pins. From the same support package is the block used for the analogue reading of current sensor.

At the current moment, a transition from the actuating state to the actuated state is based on a timer/current limitation combination. This solution can be fixed with new actuators with lower torque as a current controller can be applied to it.

For future developments, some kind of feedback to the driver so he/she knows the status of the clutches.

7.3 Critical functions

The control strategy developed for any systems is as good as its weakest link, therefore we need to make a risk analysis for the software. A FMEA is used in this project in order to find all thinkable errors and consider their effects. A FMEA has been done for the competition but is not as thoroughly as we would like it to be. The analysis is critical to be updated to new design choices in phase two.

7.4 Business model

The future car is not a sport car, or a family car or a inner city car. It is all cars at the same time. The future car is the car that can evolve and survive the climate change. Precisely as the animals evolved, the car manufacturers have to adapt to the new challenges that is presented in this century in form of lack of natural resources. The world will soon come to a point where there will be a shortfall of resources and when demand rises with increased world population, the prices will probably rise and the manufacturing costs will be affected. Therefore, the future car is the car whose chassis' and Coachbuilder's architecture is designed to be adaptable to different power- and drivetrain configuration.

The car can be build to have a certain coachbuilder that is in accordance to the customer's desires. But as the driver's daily needs changes, he or she might have to travel a longer distance to work, and then a series hybrid car is not suitable. The battery will have to be recharged and then the car runs with the combustion engine, which isn't fuel efficient as a parallel hybrid car. With an adaptable car, the car can be reconfigured into a parallel hybrid car by changing the powertrain configuration and change the motors or/and the combustion engine and other components. This can be done if the car manufacturers can simulate and test run the car by using different tools that support model based programming. This approach has a major benefit as it will enable a quick development process through MiL, SiL, PiL, and HiL tests. Another benefit is that the car can be reused, which makes it possible to have a base to build upon and only change some parts of the car's system. Users invests a lot of time and money on their cars, making it not financial viable to buy a new car due to lock in features in the car. Currently the car architecture is not designed to be adaptable to future requirements. The mechanical and hydraulic parts in have come to a point where they do not contribute to the car's innovative features. Most developments in the car industry come from innovation in the electronics and technological improvements. It is a very interesting question to analyse, as it requires standardisation in manufacturing the motors and designing the electrical parts with consideration of future development. The vision is to make car with good chassis and carrosserie compatible to new innovation.

8 The competition

In this section we will describe the last stage of the first phase of this project, which is the Shell Eco marathon at Rotterdam. The members activities and the results of the race will be described. The decision to document the project is based on two reasons: to suggest improvement for next year and to investigate if the FMEA we developed helped in reacting to challenges during/between the races. This section can be used by students of the next Eco Cars project to read in order to prepare for the competition. In order to make the hand over to next generation, a user guide for the car, the main model, the time schedule for the HK-course and a package list is included in the appendix.

8.1 The event description

The team arrived at Rotterdam just before 09.00 am on Wednesday the 20th of may 2015, which was a strategic good time to arrive as the registration office for the teams opens at 09.00 am. This allowed the whole ElBa team to make all the formal inquiries and even move the stuff from the bus to the paddock before 10.00 am. Thereafter, the mandatory briefing for the team leader and the drivers started at 10.00, which was convenient. The whole day was spent on setting up ElBa and preparing it for the safety inspection. Moreover, some team members from the mechatronics team were outsourced to Sleipner in order to help with the electrical parts in the car. The motor driver and the microcontroller had to be integrated to the system in order for the car to run with the fuel cell. The fuel cell system was functional but needed integration to be able to spin the wheels. The team working with sleipner used the same agile methods as they have done for ElBa and got a Sleipner running in three days even though the knowledge about Fuel cell systems were minimal at that point.

Shell had organized and provided access to some printers, which was useful as this allows all teams to print the necessary documents needed for the safety inspection if some papers were missing.

There was another mandatory briefing on Thursday morning and were informed that the deadline for the inspection is on the very same day. Therefore the team was stressed as they had only one chance to succeed. It took the whole day to get the car inspected, as there was a lot of queue. On one of the final stations the combustion engine had to be started and show functional emergency switches. The team wasn't able to start the engine because the team was not prepared for this test. Therefore, the team took the car and went back to the paddock to analyze the technical problems. After some investigation, it was discovered that the newly implemented dead man switch was always on, which explains why the engine didn't start. After rechecking the system and starting the motor in the paddock the car was taken back to the safety inspection and this time the team was prepared. The necessary tools were brought and the bench that ElBa stood on. The wheels could be easily spun by hand and the combustion engine start.ed The functionality of the three safety switches was demonstrated and was verified. The mechatronics team encountered some problems with the clutches actuators and had to calibrate them in order to move the clutches the precise distance (which is in mm). Just the clutch actuator system is a project in itself and the people working on it had solved it with many different and advanced solutions. There is still a lot of future work on the clutch system and the work will continue into phase two. Before the team had got through the inspection, many loose wires had to be fixed and the burnt H-bridges that broke under some of the tests were changed. But after all the small fixes the car passed the inspection.

On Friday ElBa hit the track for the first time, it made it through all 10 laps. The car had an average speed of 27 km/h and ran the race under 36 minutes. The second race lasted for only three and a half lap and then the angel gear broke. This was not unexpected, as we had previously experienced problems with the angel gear. However, the reason behind the breakage was due to some loose connectors in the decoder that was used to calculate when the injection to the motor was to be preformed. This fault was discovered on Sunday as the whole team thought that the angel gear broke due to vibrations, as this was the main reason the angle gear broke previously. This issue was discovered in a late stage and considering the time the team leaders decided to call off the third and last run. The head engineer of the ICE estimated how many hours the technical problems would have taken to fix and concluded that they wouldn't have been able to fix them on time. Furthermore, the mechatronics team had promised to be in KTH at 14.00 the next day in order to attend the mandatory reflection day and to keep the plan the team packed their things and cleaned the paddocks. By 14.00 pm the team was ready to leave the event. The bus eventually left at 17.00 due to the long queue and the inefficient cooperation of the Shell staff at site. The ElBa team did not stay for the innovation price ceremony as it would go on for many hours and the team had to stick to the time plan to ensure that the bus arrives in KTH on time, even though we were nominees for the innovation price for the deign and complexity of our hybrid car. But for next year, it is recommended to have the reflection day on another day as the end ceremony could be seen as a good closure for the project and a great stress release moment.

8.2 The race results

The results from the second run were important to compare to the first run, as the control strategy used was different. First of all, in the second attempt the small motor was used, which wasn't the case with the first attempt. The reason for this was to reduce reduce the risk of the clutch system failing so the big electric motor was engaged the whole time and therefore drove ElBa as a parallel hybrid car. Second of all, the control system for the clutch actuators was modified and the mechatronics team was excited to see if the new system works. Even though the second attempt did not last 10 laps, the results were important for us. The fuel consumed could be calculated as the Shell staff measured the level of fuel after the race. The time of each lap was also documented by Shell and through the data logged from the tablet the mechatronics team could calculate that the fuel consumption with the new control strategy was more efficient. The distance the car would have achieved had the angel gear survived, was 133 km/L. The first and valid attempt gave us 96 km/L. This leads to the conclusion that that the complex hybrid car that the team built is more efficient than the parallel hybrid configuration.

9 Conclusion and discussion

With the result at hand it is motivated to conclude that the first part of the project is a success at the very least. Considering that Elba went from being merely an empty shell to being a full-fledged complex HEV that is possible to make its way around the track of Shell's Eco-marathon the project goal for the first part was exceeded. The development time for Elba is stretched out from the second week of February till the last week of May and is yet another piece of evidence that the management, processes, and communication has effectively steered the project in the right direction.

The use of scrum in the project helps the development of ever changing systems such as when working with prototype designing and manufacturing. This is strongly recommended. Key factors such as agile decision making, involvement of all project members, and system overview enables the full exploitation of available working force, but also the technology at hand. This is due to the expansive research that has to be conducted in order to make agile decisions that do not stay within the same decision space as the previous sprints.

The use of time plans at the right level of detail has also played a part in the results achieved. The planning of the entire project has carefully been reevaluated, rechecked towards stakeholders and other subsystem teams, and replanned according to the spirit of agile development and the changing and intricately complex dependencies that Elba is constrained with (power demands, efficiencies, dependencies, safety, space and volume demands being only a handful of the many demands that has been faced and to the possible extent also met).

Having a good overview of such a project also requires control as in any system that is desired to achieve a certain result within some constraints. For this we have implemented a strong leadership echelons to which all of the subsystem teams are subject to. The response of this decision is that changes are communicated to all systems as soon as they are made since all representatives from each group immediately are informed. However, the decisions themselves are not taken solely or exclusively or even finally by a single-person-instance. Instead, the decisions are brought to the system level that holds the right knowledge to perform the decision in an effective and time optimized way.

In order to evaluate its efficiency, the project structure used for the Elba project can be compared with the work carried through on its sister vehicle Sleipner. Since the project structure are different between the two vehicles and the team members are not from the same background some aspects will not surprisingly be different. Despite the difference it is still possible to compare the necessary elements that makes up the foundation of fast prototype vehicle design and manufacturing.

Starting with the cross-subsystem and cross-domain communication in between teams within the same project, Elba shows great improvement from earlier methods still implemented on Sleipner. The project team of Elba has during this project definitely changed the norm of how student dominated projects communicates internally and externally within the Eco Cars project with great success and with smooth conflict handling and efficient work generating zeal for all participants to strive for a complete project rather than greater subsystem. This despite the fact that no teams engaged or affected by the project acquired any rewards for its completion, such as grades or credits, which is in itself a strong indication of rewarding labor within the project motivating its participants. The same thing is harder to see in the project of Sleipner with the limited insight in its project phases and development. However the end result, working environment, and atmosphere indicate that a method not as effective as described in the Elba project has been implemented. This seems to have hindered the overall systems performance and reliability, but more importantly the ability to adapt to changes and unexpected events, which is in itself contradicting since it is rather expected from fast paced prototype projects.

Secondly the lack of control permeates the Sleipner project. This affects both governing instances in the management but also down to technical level and during execution. When tasked with the development of a control system designed to be improved by later generations of the Elba team, the mechatronics team have taken it to a more extensive scope than what might have been intended in the beginning. However, this is done without impairing the end result of the initial goal. By designing a functioning and flexible control of the car and almost all of its functions and power regenerating sources (excluding the lowest level of control of the gasoline engine) the team has succeeded in its task given from the company client. This control also enables instant changes and their direct deployment down to the vehicle control, which empower other systems to be directly tested after the time it takes to compile code onto the target software, which in the current case of Elba takes under half a minute. Furthermore the control of the whole project has been taken under the wings of the mechatronics group who has acted as integration engineers for the entire system and its subsystem. This includes not exclusively design guidance of other system components, architectures, and interfaces, liaison in between sub teams, and on target and accurate execution of the project delivery. For Sleipner, which is missing engineering students of multidisciplinary knowledge this was much harder. It is safe to say that without the help of this kind of knowledge and expertise from the mechatronics team from Elba their project would not have succeeded in producing the results they achieved. This goes for both technical control of power distribution and control for the drivetrain, but also the cross-domain knowledge possessed by the teams in Elba.

Continuing with the Elba project is more than recommended and will if the current working method is enforced by internal reflections and improvements advance towards a desired outcome for all parties involved. The future advance of the project should however be adjusted according to the findings at the time of the submission of this report to make sure that the success rate stays at its current high level or keep increasing. Some of the following corrections are this far considered extremely vital for the project to proceed in its current trajectory.

A more focused work effort on the hardware of the integrated subsystem in the vehicle needs to be addressed. This is a direct and rational result of the events during the competition, but also from earlier events. For the system to perform as anticipated and to be at all controllable the failures that has already appeared has to be dealt with. The most critical failure is thus the robustness of the hardware and represents the mission critical adjustment. This means that wiring, printed circuit boards (PCB), and mechanical hardware needs to be once again analyzed, evaluated, and then corrected if necessary since it is otherwise impossible to predict the behavior of Elba and its hybrid control system. Non-predictable behavior for Elba has proven to be both devastating, causing failures, damage, and permanent damages throughout the entire chain of systems, subordinate and commanding operations. This is also in the interest of the company client for the reason that this will allow future work to be performed safely and efficiently if that work follows the guidelines that are to be created by the proceeding investigations in the next phase of the project. This includes investigation of error handling, vibration minimization and/or rejection, and continued system software integration (to minimize risk of latent software versions within the different subsystems which have a high risk of damaging the system or even pose as hazards for those who operate it). Especially the risk of hazards is a strong proof that this must be tackled in some way in the future, rather sooner than later.

Following the previous argument the continued research of the control system of Elba will continue, however it will do so with a slightly updated approach. Instead of trying to optimize Elba's fuel efficiency the control system should be optimized to be able to tackle Elba's different behaviors while considering the fuel losses whilst doing so. This way Elba will avoid being damaged from unknown operations from optimization attempts and also be able to participate in future Shell Eco-marathon. Another implication of this is that the same architecture and control should with minimal changes be implementable on other systems, such as upcoming Sleipner designs, serving both company client and course goal and requests of modularity and flexibility rather than complete optimization for single attempts or races.

Furthermore, the production of documentation and teaching material should be accelerated from the current rate. This is done to satisfy the end goal and the continued exploration of the development delivered system. This material will also serve a well explained and comprehensive description of the performed activities during the project to act as a foundation for course credits and grades.

References

[1] Bernd M. Baumann, Gregory Washington, Bradley C. Glenn, and Giorgio Rizzoni. *Mechatronic Design and Control of Hybrid Electric Vehicles.* IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 5, 2000

[2] Rui Wang and Srdjan M. Lukic. *Dynamic Programming Technique in Hybrid Electric Vehicle Optimization.* IEEE International Electric Vehicle Conference,2012

[3] J. Kang, I. Kolmanovsky, and J. W. Grizzle. *Dynamic optimization of lean burn engine aftertreatment.* University of Michigan.

[4] Zander, Justyna *Model-based Testing of Real-Time Embedded Systems in the Automotive Domain*

[5] Dotton, turner *Learning a programme context: An exploratory investigation of drivers and constrains* University of Cologne,2012

[6] Prencipe, Tell *Inter-project learning: process and outcomes of knowledge codification in project-based firms* University of Sussex,2001

[7] Kirstan, Zimmermann *Evaluating costs and benefits of model-based development of embedded software systems in the car industry - Results of qualatitaive Case Study*

[8] Smith, Prabhu, Friedman *Best Practices for Establishing a Model-Based Design Culture*

[9] Broy, Kirstan, Krcmar, Schätz, Zimmerman *What is the benefit of a model-based design of embedded software systems in the car industry?*

[10] S. Halbach, P. Sharer, S. Pagerit, C. Folkerts, A. Rousseau *Model Architecture, Methods, and Interfaces for Efficient Math-Based Design and Simulation of Automotive Control Systems* Argonne National Laboratory

[11] *Peter sandberg, Application Engineering Manager at Mathworks in Stockholm, Sweden*

[12] $https://www.gtisoft.com/applications/a_Acoustics.php$

[13] *http://www.plm.automation.siemens.com, retrieved in 04-05-2015.*

[14] *Kamil Çag˘atay Bayindir and Mehmet Ali Gözüküçük, and Ahmet Teke, A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units, Çukurova University, Department of Electrical and Electronics Engineering, Balcali, Saricam, Adana, Turkey*

[15] *K.T. Chau and Y.S. Wong, Overview of power management in hybrid electric vehicles, Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong*

[16] *Johan Fjällman, GT-Power Report, KTH Mechanics, SE-100 44 Stockholm, Sweden*

[17] $http : //www.plm.automation.siemens.com/en_us/products/lms/imagine - lab/amesim/platform/software - interfaces.shtml, retrievedat13may2015$

[18] Bo Gu, B.Eng. *Supervisory control strategy* Ohio State University, 2006

[19] Hofman, T. and Steinbuch, M. *Rule-based energy management strategies for hybrid vehicles* Int. J. Electric and Hybrid Vehicles, Vol. 1, No. 1, 2007

[20] Sciarretta, A.,Back, M. and Guzzella, L. *Optimal Control of Parallel Hybrid Electric Vehicles* IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 12, NO. 3, MAY 2004

[21] A. Chasse, A. Sciarretta *Supervisory control of hybrid powertrains: An experimental benchmark of offline optimization and online energy management* Control Engineering Practice 19 (2011) 1253–1265, IFP Energies Nouvelles, Rueil Malmaison 92500,France

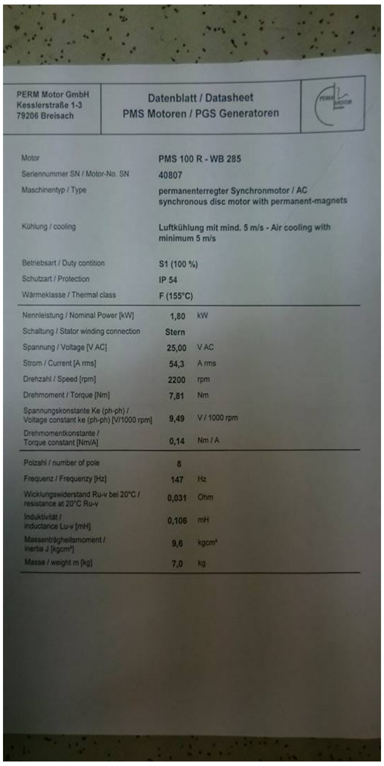
[22] J.T.B.A. Kessels[1], M.W.T. Koot[2], P.P.J. van den Bosch[1] *Optimal Adaptive Solution to Powersplit Problem in Vehicles with Integrated Starter/Generator* Technische Universiteit Eindhoven [1]Dept. of Electrical Engineering, [2]Dept. of Mechanical Engineering, The Netherlands

[23] Michiel Koot, J. T. B. A. Kessels, Student Member, IEEE, Bram de Jager, W. P. M. H. Heemels, P. P. J. van den Bosch, Member, IEEE, and Maarten Steinbuch, Senior Member, IEEE *Energy Management Strategies for Vehicular Electric Power Systems* IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 54, NO. 3, MAY 2005

10 Appendix

10.1 Appendix A1

The datasheet of the inmotions motor:



PERM Motor GmbH
Kesslerstraße 1-3
79206 Breisach

Datenblatt / Datasheet
PMS Motoren / PGS Generatoren

Motor	PMS 100 R - WB 285	
Seriennummer SN / Motor-No. SN	40807	
Maschinentyp / Type	permanenterregter Synchronmotor / AC synchronous disc motor with permanent-magnets	
Kühlung / cooling	Luftkühlung mit mind. 5 m/s - Air cooling with minimum 5 m/s	
Betriebsart / Duty contition	S1 (100 %)	
Schutzart / Protection	IP 54	
Wärmeklasse / Thermal class	F (155°C)	
Nennleistung / Nominal Power [kW]	1,80	kW
Schaltung / Stator winding connection	Stern	
Spannung / Voltage [V AC]	25,00	V AC
Strom / Current [A rms]	54,3	A rms
Drehzahl / Speed [rpm]	2200	rpm
Drehmoment / Torque [Nm]	7,81	Nm
Spannungskonstante Ke (ph-ph) / Voltage constant ke (ph-ph) [V/1000 rpm]	9,49	V / 1000 rpm
Drehmomentkonstante / Torque constant [Nm/A]	0,14	Nm / A
Polzahl / number of pole	8	
Frequenz / Frequenzy [Hz]	147	Hz
Wicklungswiderstand Ru-v bei 20°C / resistance at 20°C Ru-v	0,031	Ohm
Induktivität / inductance Lu-v [mH]	0,106	mH
Massenträgheitsmoment / inertia J [kgcm²]	9,6	kgcm²
Masse / weight m [kg]	7,0	kg

10.2 Appendix A2

The datasheet of the dunkermotor motor:

AMETEK®
PRECISION MOTION CONTROL

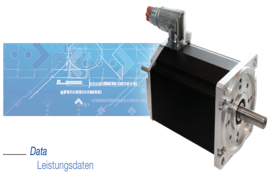
dunkermotoren
advanced motion solutions

BG 95, 650 - 1100 Watt

BLDC motor BG 95
Bürstenloser DC-Motor BG 95

- *Highly dynamic 3-phase EC motor with 8-pole neodymium magnet*
- *Available in 2 motor length*
- *Cost optimized motor design*
- *High power density and compact design make this motor suitable for numerous application areas*
- *Good price / performance ratio*
- *The motor is standard with 2 connectors*
- *Version with hall sensors for rotor position detection*
- *Optional with high resolution encoder (4x1.024 pulses per revolution) on request*
- *This motor is available in different voltage versions on request*

- Hochdynamischer 3-strängiger EC-Motor mit 8-poligem Neodymmagnet
- Verfügbar in 2 Baulängen
- Kostenoptimiertes Motordesign
- Hohe Leistungsdichte und kompakte Bauform gestatten den Einsatz in zahlreichen Anwendugsgebieten
- Gutes Preis-/ Leistungsverhältnis
- Der Motor ist standardmäßig mit 2 Anschlussstecker versehen
- Ausführung mit Hallsensoren zur Rotorlageerfassung
- Optional mit hochauflösendem Geber (4x1.024 Pulse pro Umdrehung) verfügbar
- Auf Anfrage in anderen Spannungsvarianten verfügbar



Data
Leistungsdaten

		BG 95x40			BG 95x80		
Rated voltage/ Nennspannung	VDC	24	48	60	24	48	60
Continuous rated speed/ Nenndrehzahl	rpm	3500			3500		
Continuous rated torque/ Nenndrehmoment	Ncm	180			290		
Continuous current/ Nennstrom	A	27	14	11	46	23	18
Peak stall torque/ Max. Anhaltmoment	Ncm	540			870		
Rotor inertial/ Trägheitsmoment	kgcm²	0.95			1.89		
Weight of motor/ Motorgewicht	kg	3.4			5.1		

10.3 Appendix A3

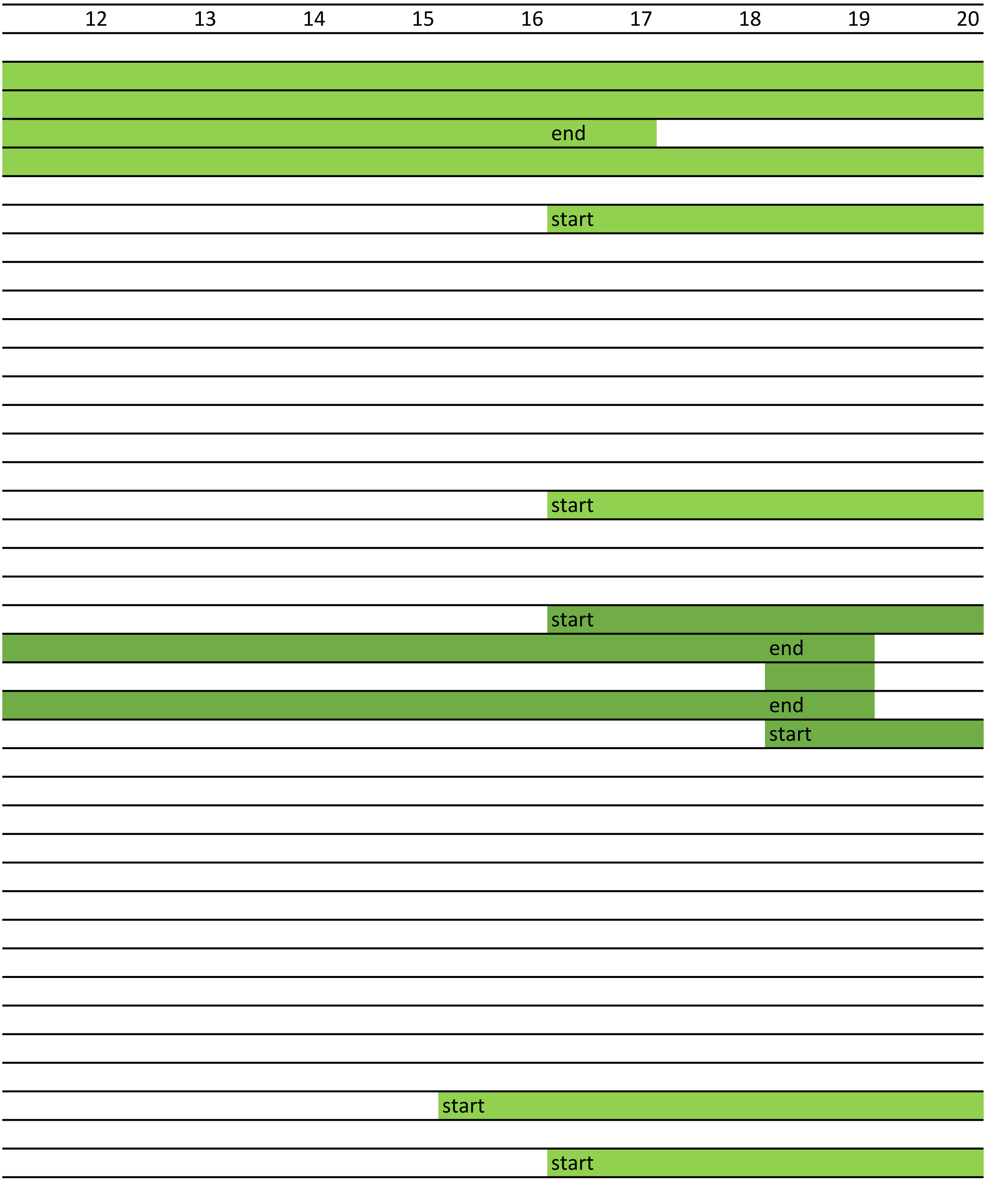
Timeplan Last updated: 17-02-2015

February V. 6

	Day:	1	2
Activity:	**Important deadlines**		
	Choose electric motor		
	"Simple" model	start	
	Serial or parallel?	start	
	Choose supercap		
	Advanced model		
	Decide low voltage electric components		
	User interface		
	Design high power supply system		
	Test log system		
	Design low power supply system		
	Testing the new hybrid drivetrain		
	Wiring		
	Checking robustnes		
	Going through old electrical system		
	Designing multidrive		
	Go through CAN bus		
	Programming		
	State-of-the-Art		
	Critical function		
	Acquire the requirements		
	spark plugs		
	order engines		
	create test rig		
	Design and making of subsystems		
	dimension for exhaust system ****		
	Modifications		
	assemble/mounting engine		
	Design and dimension		
	Tillverkning		
	Test		
	Verification of the requirements		
	Coherence of rules		
	PIAC and ODC		
	Hydraulic system and brakes		
	Rolling/driving tests		
	Arlanda test (date?)		
	Does everything fit in the car?(dimension)		
	Assemble car		
	Choose driver		
	Test rig from drivetrain		

					V. 7			
3	4	5	6	7	8	9	10	11
					start			
					start			
					start			
					start			

V. 8


12
13
14
15
16
17
18
19
20
end
start
start
start
end
end
start
start
start

		V. 9						Mars
21	22	23	24	25	26	27	28	1
		Design review						
		end						
								end
		end						
		start						
		start						
		start						
								start
								end
		start						
	end							
		start						
		start						
		end						
		start						

start

V. 10							V. 11	
2	3	4	5	6	7	8	9	10
							Design revi	Tentaperiod
start								
						end*		
						end		
						end		
							end	
							end	
							end	
						start		
						end		
start								

V. 12

	11	12	13	14	15	16	17	18	19
d							Design Review 1		

			V. 13					
20	21	22	23	24	25	26	27	28
			start					
			start					
			start					
			start					
			start					
			start					
			start					

V. 14			April				V. 15	
29	30	31	1	2	3	4	5	6
			Halftime pr	Easter				
	end							
	end							

end

						V. 16		
7	8	9	10	11	12	13	14	15
						Design review		
	start							
					end			
					end			
					end			
							start	
						end		
							start	
	start							
	start							

V. 17

16	17	18	19	20	21	22	23	24
							Design review	
						end		
						end		
						end		
						end		
				start				

		V. 18				May		
25	26	27	28	29	30	1	2	3
		Subsystem testing			First whole car test (Arlanda) and submission o			
				end				
	end							
		start						
				end				

V. 19							V. 20	
4	5	6	7	8	9	10	11	12
Second whole car test		ODC and FMEA finishec	3rd test				off track pris submissio	
								end
								end
end								
								end
		end						
								end
								end

V. 21

13	14	15	16	17	18	19	20	21
Roll out					Rehearsal	Travel to competition		Presentatio

end

			V. 22
	22	23	24	25
n				Come back as winners and state-of-art presentation

10.4 Appendix A4

Advanced Power Steering (APS)

Description

The APS – Advanced Power Steering system consists of a permanent magnet AC motor with integrated gear box and an AC Drive with an I/O interface. The APS connects directly to the steering sensors and may operate as a stand-alone system or as part of a CAN network. The product range covers a wide variety of vehicle applications including Class 1, 2, and 3 lift trucks. The APS is a good choice for replacing existing electric and hydraulic steering systems.

Features

- 4 different power ranges with three gear ratios.
- Reliable, low maintenance brushless system.
- Safe operation ensured with extensive supervision.
- CANopen interface for communication.
- Stand-alone mode allows direct connection of most steering encoders.
- Customizable software – through application programming or an extensive parameter set.
- I/O interface allows direct connection of most steering sensors.
- Quiet.
- Kollmorgen Truck Service Tool compatible.

Application

The APS provides a cost effective electric steering solution that eliminates the need for hydraulic components and/or the steering column, thereby giving increased design flexibility. The sealed construction and brushless motor design makes the APS virtually maintenance free. The APS has a range of safety capabilities that facilitate reliable EN 954-1 operation. In the unlikely event of a failure, a safety supervision system integrated into the APS can directly activate the emergency brake or bring the truck to a controlled stop via the CAN bus. In addition to this, the APS continuously reports its status to the vehicle controller. The software also allows for a variety of features such as automatic centering, steering proportional to speed, and an adjustable steering sensitivity ratio. The APS system provides excellent vehicle maneuverability and extensive diagnostic support.

CANopen

As part of the Kollmorgen vehicle system, the APS communicates via the industry standard CANopen protocol. This allows for easy integration and for different components (i.e. traction drives, truck controllers, etc.) to seamlessly function together. The system is compatible with the Kollmorgen Truck Service Tool, allowing on-location remote diagnostics and service planning.

For Immediate assistance
E-mail: sales.sth@danahermotion.com
Tel. Europe: +46 (0)8 682 6400
Tel. North America: +1 412 749-0710
Tel. Asia: +82 6222-1051
www.danahermotion.com

KOLLMORGEN®
A Danaher Motion Company

1P111120 Rev. 2 Ver. 4 Date Release: 08 Jun 2009

APS Motor Gear Performance Data

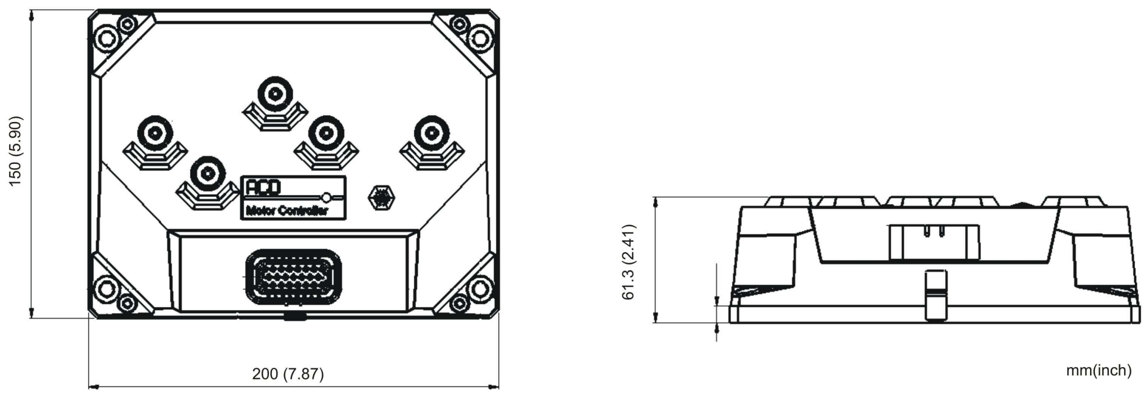
	Model		PSM-A30xx-A			PSM-B30xx-B			PSM-C50xx-D		PSM-C50xx-C	
	Battery	Vdc	24	36	48	24	36	48	24[1)]	36[1)]	48	80[1)]
		Gear Ratio										
S2 60 Min	Max speed RPM	35:1	58	58	58	58	58	58	58	58	58	58
		43:1	47	47	47	47	47	47	47	47	47	47
		51:1	40	40	40	40	40	40	40	40	40	40
	Max Torque Nm (lbft)	35:1	33 (25)	33 (25)	33 (25)	33 (25)	33 (25)	33 (25)	33 (25)	33 (25)	33 (25)	33 (25)
		43:1	41 (30)	41 (30)	41 (30)	41 (30)	41 (30)	41 (30)	41 (30)	41 (30)	41 (30)	41 (30)
		51:1	49 (36)	49 (36)	49 (36)	49 (36)	49 (36)	49 (36)	49 (36)	49 (36)	49 (36)	49 (36)
	Power W (Hp)		203 (0.27)	203 (0.27)	203 (0.27)	276 (0.37)	276 (0.37)	276 (0.37)	350 (0.47)	350 (0.47)	350 (0.47)	350 (0.47)
S2 1 min	Max speed RPM	35:1	63	100	100	37	74	100	74	100	74	100
		43:1	51	81	81	30	60	81	60	81	60	81
		51:1	43	69	69	25	51	69	51	69	51	69
	Max Torque Nm (lbft)	35:1	69 (51)	69 (51)	69 (51)	93 (69)	93 (69)	93 (69)	133 (98)	133 (98)	133 (98)	133 (98)
		43:1	85 (63)	85 (63)	85 (63)	114 (84)	114 (84)	114 (84)	163 (121)	163 (121)	163 (121)	163 (121)
		51:1	101 (74)	101 (74)	101 (74)	136 (100)	136 (100)	136 (100)	194 (143)	194 (143)	194 (143)	194 (143)
	Power W (Hp)		456 (0.61)	725 (0.97)	725 (0.97)	362 (0.49)	725 (0.97)	976 (1.31)	1036 (1.39)	1394 (1.87)	1036 (1.39)	1394 (1.87)
	Max Radial Load[3] N (lb)	35:1	2230 (501)	2110 (474)	2110 (474)	2230 (501)	2110 (474)	2110 (474)	2920 (656)	2920 (656)	2920 (656)	2920 (656)
		43:1	2390 (537)	2270 (510)	2270 (510)	2390 (537)	2270 (510)	2270 (510)	3110 (699)	3110 (699)	3110 (699)	3110 (699)
		51:1	2530 (569)	2390 (537)	2390 (537)	2530 (569)	2390 (537)	2390 (537)	3280 (737)	3280 (737)	3280 (737)	3280 (737)

Notes: 1. 24, 36 & 80 volt performance data is estimated based from 48 volt. Actual performance may vary.
2. Performance data and product offerings are subject to change without notice.
3. Max Radial Load is positioned at center of key. Load positions extended further away from bearing must be scaled accordingly.

Power stage / Technical Data

Battery Voltage, nominal	24-48, 80 VDC
Supported steering interfaces	Danaher Motion TFD, SKF steer encoder (AHE-5600 A), LORD Tactile Feedback Device (RD-2089-01)
I/O Outputs	3 Open drain outputs
I/O Inputs	4 Digital and 2 Analog inputs
Protection Class	IP65 (with mounted connector)
Communications interface	CAN (CANopen)
Connector	AMP-SEAL 23 pin (power stage)

Dimensions



10.5 Appendix A5

maxon motor

maxon motor control | ESCON Servo Controller

Hardware Reference | Edition September 2013

ESCON 50/5

Servo Controller

P/N 409510

Hardware Reference

Document ID: rel4285

maxon motor ag Brünigstrasse 220 P.O.Box 263 CH-6072 Sachseln Phone +41 41 666 15 00 Fax +41 41 666 16 50 www.maxonmotor.com

TABLE OF CONTENTS

READ THIS FIRST

These instructions are intended for qualified technical personnel. Prior commencing with any activities …

- *you must carefully read and understand this manual and*
- *you must follow the instructions given therein.*

The ESCON 50/5 is considered as partly completed machinery according to EU Directive 2006/42/EC, Article 2, Clause (g) and **is intended to be incorporated into or assembled with other machinery or other partly completed machinery or equipment**.

Therefore, you must not put the device into service, …

- *unless you have made completely sure that the other machinery fully complies with the EU directive's requirements!*
- *unless the other machinery fulfills all relevant health and safety aspects!*
- *unless all respective interfaces have been established and fulfill the herein stated requirements!*

1 About

1.1 About this Document

1.1.1 Intended Purpose

The purpose of the present document is to familiarize you with the ESCON 50/5 Servo Controller. It will highlight the tasks for safe and adequate installation and/or commissioning. Follow the described instructions …

- to avoid dangerous situations,
- to keep installation and/or commissioning time at a minimum,
- to increase reliability and service life of the described equipment.

The document contains performance data and specifications, information on fulfilled standards, details on connections and pin assignment, and wiring examples.

1.1.2 Target Audience

The present document is intended for trained and skilled personnel. It conveys information on how to understand and fulfill the respective work and duties.

1.1.3 How to use

Take note of the following notations and codes which will be used throughout the document.

Notation	Meaning
(n)	refers to an item (such as order number, list item, etc.)
➔	denotes “see”, “see also”, “take note of” or “go to”

Table 1-1 Notation used

1.1.4 Symbols & Signs

In the course of the present document, the following symbols and sings will be used.

<table>
<tr><th>Type</th><th>Symbol</th><th colspan="2">Meaning</th></tr>
<tr><td rowspan="3">Safety Alert</td><td rowspan="3">
(typical)</td><td>DANGER</td><td>Indicates an imminent hazardous situation. If not avoided, it will result in death or serious injury.</td></tr>
<tr><td>WARNING</td><td>Indicates a potential hazardous situation. If not avoided, it can result in death or serious injury.</td></tr>
<tr><td>CAUTION</td><td>Indicates a probable hazardous situation or calls the attention to unsafe practices. If not avoided, it may result in injury.</td></tr>
<tr><td>Prohibited Action</td><td>
(typical)</td><td colspan="2">Indicates a dangerous action. Hence, you must not!</td></tr>
<tr><td>Mandatory Action</td><td>
(typical)</td><td colspan="2">Indicates a mandatory action. Hence, you must!</td></tr>
</table>

Type	Symbol	Meaning	
Information		Requirement / Note / Remark	Indicates an activity you must perform prior continuing, or gives information on a particular item you need to observe.
		Best Practice	Indicates an advice or recommendation on the easiest and best way to further proceed.
		Material Damage	Indicates information particular to possible damage of the equipment.

Table 1-2 Symbols & Signs

1.1.5 Trademarks and Brand Names

For easier legibility, registered brand names are listed below and will not be further tagged with their respective trademark. It must be understood that the brands (the list below is not necessarily concluding) are protected by copyright and/or other intellectual property rights even if their legal trademarks are omitted in the later course of this document.

Brand Name	Trademark Owner
Windows®	© Microsoft Corporation, USA-Redmond, WA

Table 1-3 Brand Names and Trademark Owners

1.1.6 Copyright

maxon motor ag
Brünigstrasse 220
P.O.Box 263
CH-6072 Sachseln

Phone +41 41 666 15 00
Fax +41 41 666 16 50
Web www.maxonmotor.com

1.2 About the Device

The ESCON 50/5 is a small-sized, powerful 4-quadrant PWM servo controller for the highly efficient control of permanent magnet-activated brushed DC motors or brushless EC motors up to approximately 250 Watts.

The featured operating modes – speed control (closed loop), speed control (open loop), and current control – meet the highest requirements. The ESCON 50/5 is designed being commanded by an analog set value and features extensive analog and digital I/O functionality.

The device is designed to be configured via USB interface using the graphical user interface «ESCON Studio» for Windows PCs.

You can download the latest ESCON software version (as well as the latest edition of the documentation) from the internet under ➔http://escon.maxonmotor.com.

1.3 About the Safety Precautions

- Make sure that you have read and understood the note “READ THIS FIRST” on page A-2!
- Do not engage with any work unless you possess the stated skills (➔chapter “1.1.2 Target Audience” on page 1-3)!
- Refer to ➔chapter “1.1.4 Symbols & Signs” on page 1-3 to understand the subsequently used indicators!
- You must observe any regulation applicable in the country and/or at the site of implementation with regard to health and safety/accident prevention and/or environmental protection!

DANGER

High Voltage and/or Electrical Shock
Touching live wires causes death or serious injuries!

- *Consider any power cable as connected to life power, unless having proven the opposite!*
- *Make sure that neither end of cable is connected to life power!*
- *Make sure that power source cannot be engaged while work is in process!*
- *Obey lock-out/tag-out procedures!*
- *Make sure to securely lock any power engaging equipment against unintentional engagement and tag it with your name!*

Requirements

- *Make sure that all associated devices and components are installed according to local regulations.*
- *Be aware that, by principle, an electronic apparatus can not be considered fail-safe. Therefore, you must make sure that any machine/apparatus has been fitted with independent monitoring and safety equipment. If the machine/apparatus should break down, if it is operated incorrectly, if the control unit breaks down or if the cables break or get disconnected, etc., the complete drive system must return – and be kept – in a safe operating mode.*
- *Be aware that you are not entitled to perform any repair on components supplied by maxon motor.*

Electrostatic Sensitive Device (ESD)

- *Make sure to wear working cloth in compliance with ESD.*
- *Handle device with extra care.*

••page intentionally left blank••

2 Specifications

2.1 Technical Data

ESCON 50/5 (409510)		
Electrical Rating	Nominal operating voltage $+V_{CC}$	10…50 VDC
	Absolute operating voltage $+V_{CC\ min}$ / $+V_{CC\ max}$	8 VDC / 56 VDC
	Output voltage (max.)	0.98 x $+V_{CC}$
	Output current I_{cont} / I_{max} (<20 s)	5 A / 15 A
	Pulse Width Modulation frequency	53.6 kHz
	Sampling rate PI current controller	53.6 kHz
	Sampling rate PI speed controller	5.36 kHz
	Max. efficiency	95%
	Max. speed DC motor	limited by max. permissible speed (motor) and max. output voltage (controller)
	Max. speed EC motor	150’000 rpm (1 pole pair)
	Built-in motor choke	3 x 30 µH; 5 A
Inputs & Outputs	Analog Input 1 Analog Input 2	resolution 12-bit; –10…+10 V; differential
	Analog Output 1 Analog Output 2	resolution 12-bit; –4…+4 V; referenced to GND
	Digital Input 1 Digital Input 2	+2.4…+36 VDC (R_i = 38.5 kΩ)
	Digital Input/Output 3 Digital Input/Output 4	+2.4…+36 VDC (R_i = 38.5 kΩ) / max. 36 VDC (I_L <500 mA)
	Hall sensor signals	H1, H2, H3
	Encoder signals	A, A\, B, B\, (max. 1 MHz)
Voltage Outputs	Auxiliary output voltage	+5 VDC (I_L ≤10 mA)
	Hall sensor supply voltage	+5 VDC (I_L ≤30 mA)
	Encoder supply voltage	+5 VDC (I_L ≤70 mA)
Potentiometers	Potentiometer P1 (on board) Potentiometer P2 (on board)	240°; linear
Motor Connections	DC motor	+ Motor, – Motor
	EC motor	Motor winding 1, Motor winding 2, Motor winding 3
Interface	USB 2.0	full speed (12 Mbit/s)
Status Indicators	Operation	green LED
	Error	red LED

ESCON 50/5 (409510)			
Physical	Weight	approx. 204 g	
	Dimensions (L x W x H)	115 x 75.5 x 24 mm	
	Mounting holes	for M4 screws	
Environmental Conditions	Temperature	Operation	–30…+45°C
		Extended range *1)	+45…+85°C Derating: –0.113 A/°C
		Storage	–40…+85°C
	Humidity	20…80% (condensation not permitted)	

Remark: *1) Operation within the extended temperature range is permitted. However, a respective derating (declination of max. output current) as to the stated value will apply.

Table 2-4 Technical Data

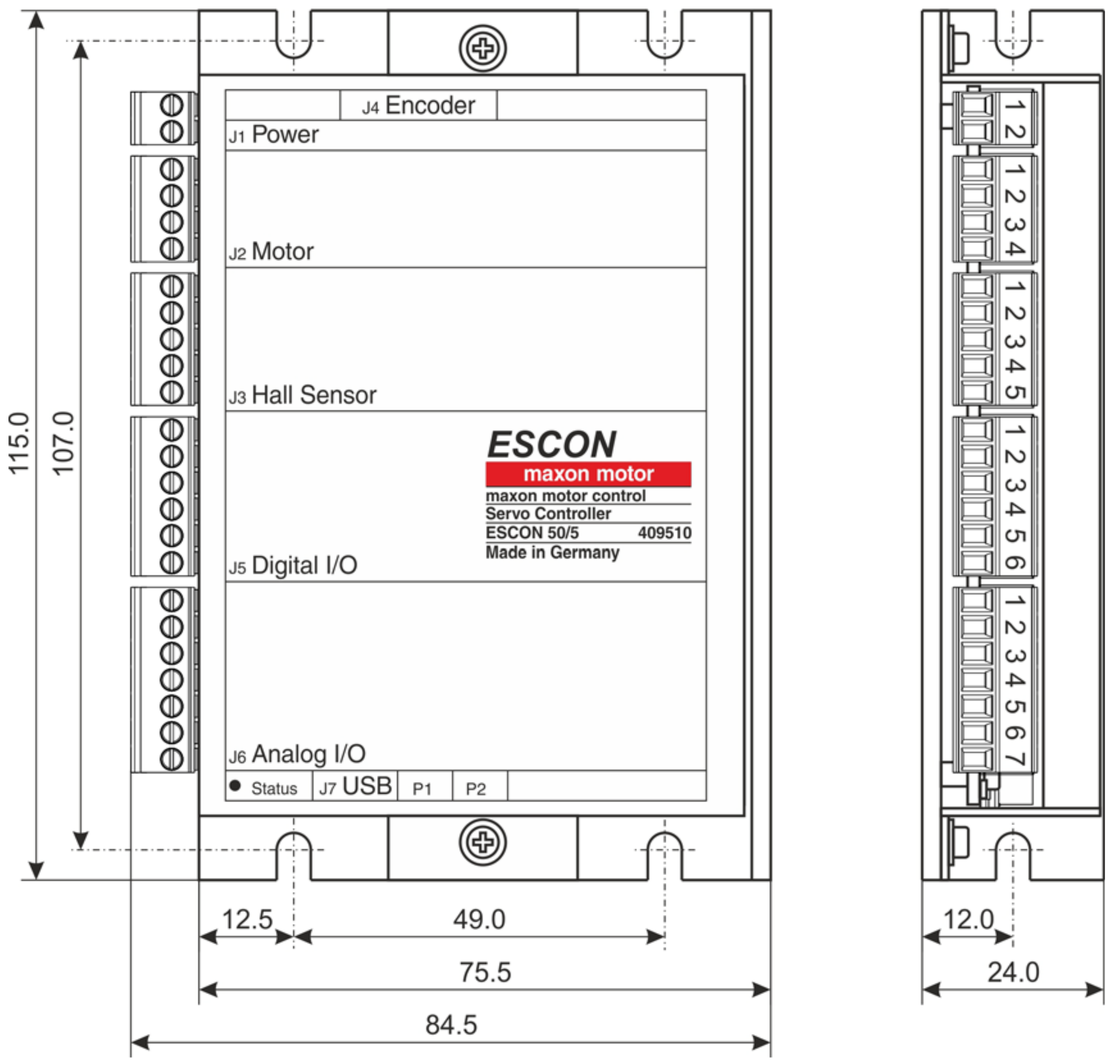


Figure 2-1 Dimensional Drawing [mm]

2.2 Standards

The described device has been successfully tested for compliance with the below listed standards. In practical terms, only the complete system (the fully operational equipment comprising all individual components, such as motor, servo controller, power supply unit, EMC filter, cabling etc.) can undergo an EMC test to ensure interference-free operation.

Important Notice
The device's compliance with the mentioned standards does not imply its compliance within the final, ready to operate setup. In order to achieve compliance of your operational system, you must perform EMC testing of the involved equipment as a whole.

Electromagnetic Compatibility		
Generic Standards	IEC/EN 61000-6-2	Immunity for industrial environments
	IEC/EN 61000-6-3	Emission standard for residential, commercial and light-industrial environments
Applied Standards	IEC/EN 61000-6-3 IEC/EN 55022 (CISPR22)	Radio disturbance characteristics / radio interference
	IEC/EN 61000-4-2	Electrostatic discharge immunity test 8 kV/6 kV
	IEC/EN 61000-4-3	Radiated, radio-frequency, electromagnetic field immunity test >10 V/m
	IEC/EN 61000-4-4	Electrical fast transient/burst immunity test ±2 kV
	IEC/EN 61000-4-6	Immunity to conducted disturbances, induced by radio-frequency fields 10 Vrms

Others		
Environmental Standards	IEC/EN 60068-2-6	Environmental testing – Test Fc: Vibration (sinusoidal)
	MIL-STD-810F	Random transport
Safety Standards	UL File Number E207844; unassembled printed circuit board	

Table 2-5 Standards

••page intentionally left blank••

3 Setup

IMPORTANT NOTICE: PREREQUISITES FOR PERMISSION TO COMMENCE INSTALLATION

The ESCON 50/5 is considered as partly completed machinery according to EU Directive 2006/42/EC, Article 2, Clause (g) and **is intended to be incorporated into or assembled with other machinery or other partly completed machinery or equipment**.

WARNING

Risk of Injury

Operating the device without the full compliance of the surrounding system with the EU Directive 2006/42/EC may cause serious injuries!

- *Do not operate the device, unless you have made completely sure that the other machinery fully complies with the EU directive's requirements!*
- *Do not operate the device, unless the other machinery fulfills all relevant health and safety aspects!*
- *Do not operate the device, unless all respective interfaces have been established and fulfill the requirements stated in this document!*

3.1 Generally applicable Rules

Maximal permitted Supply Voltage

- *Make sure that supply power is between 10…50 VDC.*
- *Supply voltages above 56 VDC, or wrong polarity will destroy the unit.*
- *Note that the necessary output current is depending on the load torque. Yet, the output current limits of the ESCON 50/5 are as follows; continuous max. 5 A / short-time (acceleration) max. 15 A.*

3.2 Determination of Power Supply

Basically, any power supply may be used, provided it meets the minimal requirements stated below.

Power Supply Requirements	
Output voltage	$+V_{CC}$ 10…50 VDC
Absolute output voltage	min. 8 VDC; max. 56 VDC
Output current	Depending on load (continuous max. 5 A; short-time (acceleration) max. 15 A (<20 s)

1) Use the formula below to calculate the required voltage under load.
2) Choose a power supply according to the calculated voltage. Thereby consider:
   a) During braking of the load, the power supply must be capable of buffering the recovered kinetic energy (for example, in a capacitor).
   b) If you are using an electronically stabilized power supply, make sure that the overcurrent protection circuit is configured inoperative within the operating range.

Note
The formula already takes the following into account:
- *Maximum PWM duty cycle of 98%*
- *Controller's max. voltage drop of 1 V @ 5 A*

KNOWN VALUES:
- Operating torque M [mNm]
- Operating speed n [rpm]
- Nominal motor voltage U_N [Volt]
- Motor no-load speed at U_N, n_0 [rpm]
- Speed/torque gradient of the motor $\Delta n / \Delta M$ [rpm/mNm]

SOUGHT VALUE:
- Supply voltage $+V_{CC}$ [Volt]

SOLUTION:

$$V_{CC} \geq \left[\frac{U_N}{n_O} \cdot \left(n + \frac{\Delta n}{\Delta M} \cdot M\right) \cdot \frac{1}{0.98}\right] + 1[V]$$

3.3 Connections

The actual connection will depend on the overall configuration of your drive system and the type of motor you will be using.

Follow the description in given order and choose the connection scheme that suits the respective components you are using. For corresponding wiring diagrams ➔chapter “4 Wiring” on page 4-29.

3.3.1 Power (J1)

Figure 3-2 Power Plug J1

J1 Pin	Signal	Description
1	Power_GND	Ground of supply voltage
2	$+V_{CC}$	Power supply voltage (+10…+50 VDC)

Table 3-6 Power Plug J1 – Pin Assignment

Specification / Accessories	
Type	Pluggable screw-type terminal block, 2 poles, pitch 3.5 mm
Suitable cables	0.14…1.5 mm² multi-core, AWG 28-14 0.14…1.5 mm² single wire, AWG 28-14

Table 3-7 Power Plug J1 – Specification & Accessories

3.3.2 Motor (J2)

The servo controller is set to drive either maxon DC motor (brushed) or maxon EC motor (brushless).

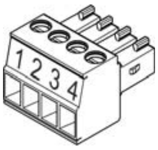


Figure 3-3 Motor Plug J2

J2 Pin	Signal	Description
1	Motor (+M)	DC motor: Motor +
2	Motor (–M)	DC motor: Motor –
3	not connected	–
4	Motor shield	Cable shield

Table 3-8 Motor Plug J2 – Pin Assignment for maxon DC motor (brushed)

J2 Pin	Signal	Description
1	Motor winding 1	EC motor: Winding 1
2	Motor winding 2	EC motor: Winding 2
3	Motor winding 3	EC motor: Winding 3
4	Motor shield	Cable shield

Table 3-9 Motor Plug J2 – Pin Assignment for maxon EC motor (brushless)

Specification / Accessories	
Type	Pluggable screw-type terminal block, 4 poles, pitch 3.5 mm
Suitable cables	0.14…1.5 mm^2 multi-core, AWG 28-14 0.14…1.5 mm^2 single wire, AWG 28-14

Table 3-10 Motor Plug J2 – Specification & Accessories

3.3.3 Hall Sensor (J3)

Suitable Hall effect sensors IC use «Schmitt trigger» with open collector output.

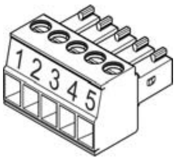


Figure 3-4 Hall Sensor Plug J3

J3 Pin	Signal	Description
1	Hall sensor 1	Hall sensor 1 input
2	Hall sensor 2	Hall sensor 2 input
3	Hall sensor 3	Hall sensor 3 input
4	+5 VDC	Hall sensor supply voltage (+5 VDC; I_L ≤30 mA)
5	GND	Ground

Table 3-11 Hall Sensor Plug J3 – Pin Assignment

Specification / Accessories	
Type	Pluggable screw-type terminal block, 5 poles, pitch 3.5 mm
Suitable cables	0.14…1.5 mm² multi-core, AWG 28-14 0.14…1.5 mm² single wire, AWG 28-14

Table 3-12 Hall Sensor Plug J3 – Specification & Accessories

Hall sensor supply voltage	+5 VDC
Max. Hall sensor supply current	30 mA
Input voltage	0…24 VDC
Max. input voltage	+24 VDC
Logic 0	typically <1.0 V
Logic 1	typically >2.4 V
Internal pull-up resistor	2.7 kΩ (against +5.45 V – 0.6 V)

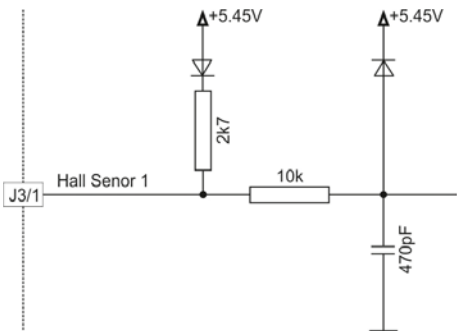


Figure 3-5 Hall Sensor 1 Input Circuit (analogously valid also for Hall Sensors 2 & 3)

3.3.4 Encoder (J4)

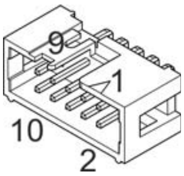


Figure 3-6 Encoder Socket J4

J4 Pin	Signal	Description
1	not connected	–
2	+5 VDC	Encoder supply voltage (+5 VDC; ≤70 mA)
3	GND	Ground
4	not connected	–
5	Channel A\	Channel A complement
6	Channel A	Channel A
7	Channel B\	Channel B complement
8	Channel B	Channel B
9	not connected	–
10	not connected	–

Table 3-13 Encoder Socket J4 – Pin Assignment

Accessories		
Suitable strain relief	Retainer	For sockets with strain relief: 1 retainer clip, height 13.5 mm, 3M (3505-8110)
		For sockets without strain relief: 1 retainer clip, height 7.9 mm, 3M (3505-8010)
	Latch	For sockets with strain relief: 2 pieces, 3M (3505-33B)

Table 3-14 Encoder Socket J4 – Accessories

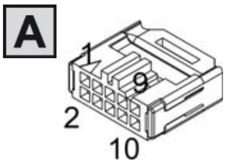
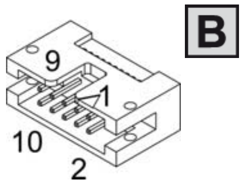
Encoder Cable (275934)	
	
Cable cross-section	10 x AWG28, round-jacket, twisted pair flat cable, pitch 1.27 mm
Length	3.20 m
Head A	DIN 41651 female, pitch 2.54 mm, 10 poles, with strain relief
Head B	DIN 41651 Plug, pitch 2.54 mm, 10 poles, with strain relief

Table 3-15 Encoder Cable

Best Practice

- *Because of its resistance against electrical interferences,* ***we recommend using differential scheme****. Nevertheless, the controller supports both schemes – differential and single-ended.*
- *The controller does not require an index impulse (Ch I, Ch I\).*
- *For best performance,* ***we strongly recommend using encoders with line driver****. Otherwise, speed limitations may apply due to slow switching edges.*

Differential	
Min. differential input voltage	±200 mV
Max. input voltage	+12 VDC / –12 VDC
Line receiver (internal)	EIA RS422 Standard
Max. input frequency	1 MHz

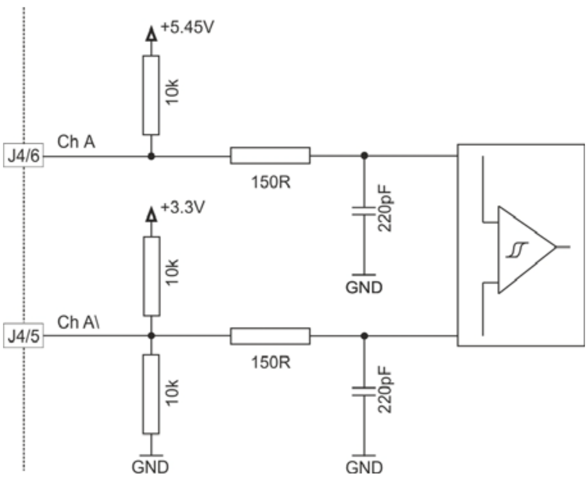


Figure 3-7 Encoder Input Circuit Ch A “Differential” (analogously valid also for Ch B)

Single-ended	
Input voltage	0…5 VDC
Max. input voltage	+12 VDC / –12 VDC
Logic 0	<1.0 V
Logic 1	>2.4 V
Input high current	I_{IH} = typically –50 µA @ 5 V
Input low current	I_{IL} = typically –550 µA @ 0 V
Max. input frequency	100 kHz

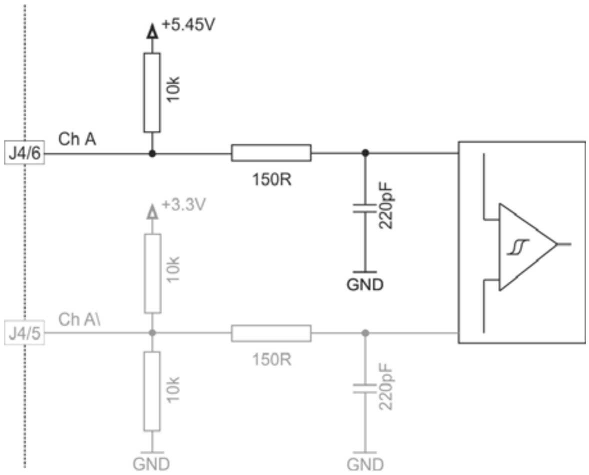


Figure 3-8 Encoder Input Circuit Ch A “Single-ended” (analogously valid also for Ch B)

3.3.5 Digital I/Os (J5)

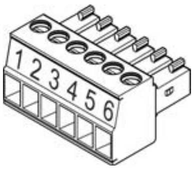


Figure 3-9 Digital I/Os Plug J5

J5 Pin	Signal	Description
1	DigIN1	Digital input 1
2	DigIN2	Digital input 2
3	DigIN/DigOUT3	Digital input/output 3
4	DigIN/DigOUT4	Digital input/output 4
5	GND	Signal ground
6	+5 VDC	Auxiliary output voltage (+5 VDC; ≤10 mA)

Table 3-16 Digital I/Os Plug J5 – Pin Assignment & Cabling

Specification / Accessories	
Type	Pluggable screw-type terminal block, 6 poles, pitch 3.5 mm
Suitable cables	0.14…1.5 mm² multi-core, AWG 28-14 0.14…1.5 mm² single wire, AWG 28-14

Table 3-17 Digital I/Os Plug J5 – Specification & Accessories

3.3.5.1 Digital Input 1

Input voltage	0…36 VDC
Max. input voltage	+36 VDC / –36 VDC
Logic 0	typically <1.0 V
Logic 1	typically >2.4 V
Input resistance	typically 47 kΩ (<3.3 V) typically 38.5 kΩ (@ 5 V) typically 25.5 kΩ (@ 24 V)
Input current at logic 1	typically 130 μA @ +5 VDC
Switching delay	<8 ms

PWM frequency range	10 Hz…5 kHz
PWM duty cycle range	10...90%

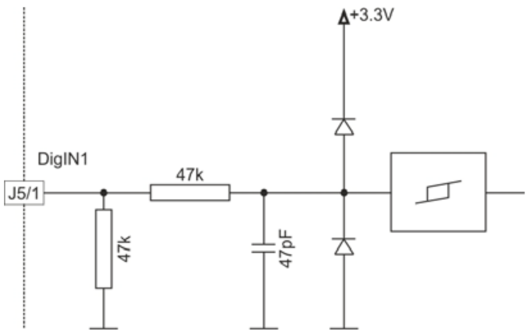


Figure 3-10 DigIN1 Circuit

3.3.5.2 Digital Input 2

Input voltage	0…36 VDC
Max. input voltage	+36 VDC / –36 VDC
Logic 0	typically <1.0 V
Logic 1	typically >2.4 V
Input resistance	typically 47 kΩ (<3.3 V) typically 38.5 kΩ (@ 5 V) typically 25.5 kΩ (@ 24 V)
Input current at logic 1	typically 130 μA @ +5 VDC
Switching delay	<8 ms

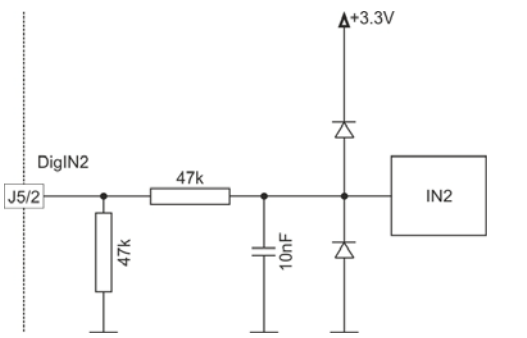


Figure 3-11 DigIN2 Circuit

3.3.5.3 Digital Inputs/Outputs 3 and 4

DigIN	
Input voltage	0…36 VDC
Max. input voltage	+36 VDC
Logic 0	typically <1.0 V
Logic 1	typically >2.4 V
Input resistance	typically 47 kΩ (<3.3 V) typically 38.5 kΩ (@ 5 V) typically 25.5 kΩ (@ 24 V)
Input current at logic 1	typically 130 µA @ +5 VDC
Switching delay	<8 ms

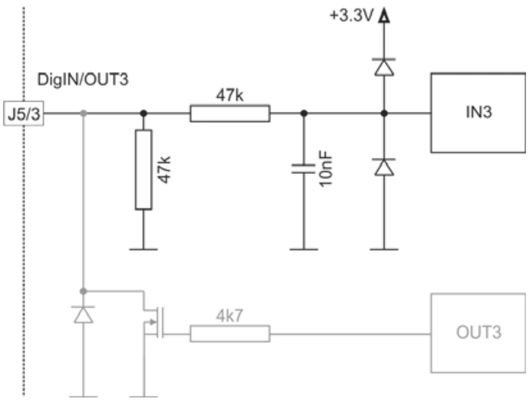


Figure 3-12 DigIN3 Circuit (analogously valid also for DigIN4)

DigOUT	
Max. input voltage	+36 VDC
Max. load current	500 mA
Max. voltage drop	0.5 V @ 500 mA
Max. load inductance	100 mH @ 24 VDC; 500 mA

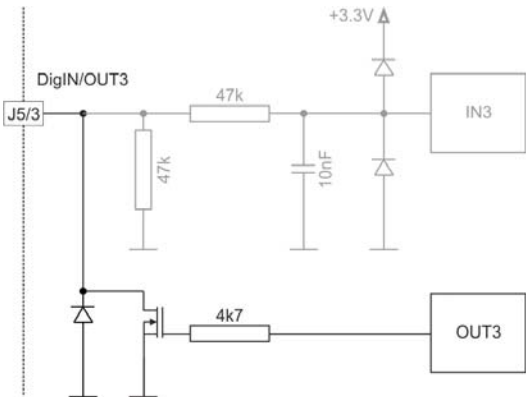


Figure 3-13 DigOUT3 Circuit (analogously valid also for DigOUT4)

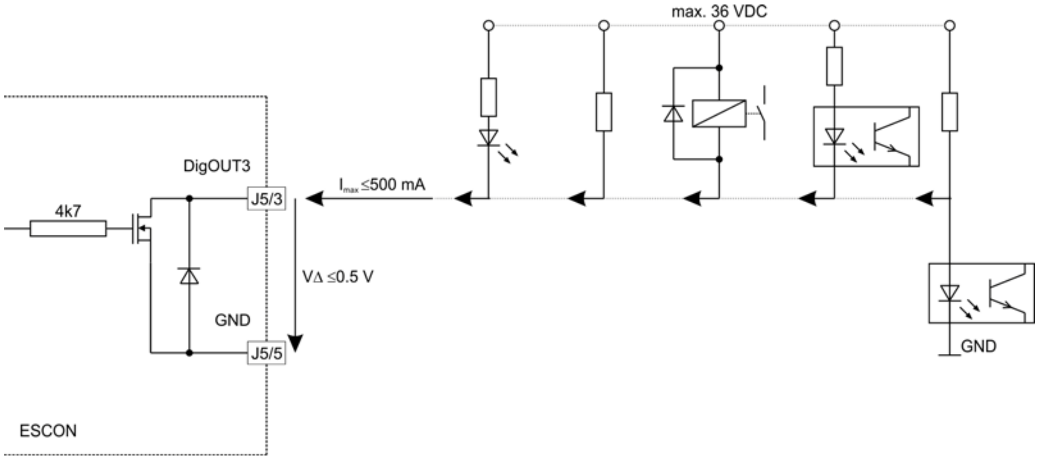


Figure 3-14 DigOUT3 Wiring Examples (analogously valid also for DigOUT4)

3.3.6 Analog I/Os (J6)

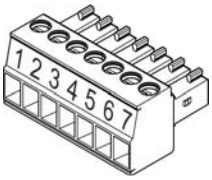


Figure 3-15 Analog I/Os Plug J6

J6 Pin	Signal	Description
1	AnIN1+	Analog input 1, positive signal
2	AnIN1–	Analog input 1, negative signal
3	AnIN2+	Analog input 2, positive signal
4	AnIN2–	Analog input 2, negative signal
5	AnOUT1	Analog output 1
6	AnOUT2	Analog output 2
7	GND	Signal ground

Table 3-18 Analog I/Os Plug J6 – Pin Assignment & Cabling

Specification / Accessories	
Type	Pluggable screw-type terminal block, 7 poles, pitch 3.5 mm
Suitable cables	0.14…1.5 mm² multi-core, AWG 28-14 0.14…1.5 mm² single wire, AWG 28-14

Table 3-19 Analog I/Os Plug J6 – Specification & Accessories

3.3.6.1 Analog Inputs 1 and 2

Input voltage	–10…+10 VDC (differential)
Max. input voltage	+24 VDC / –24 VDC
Common mode voltage	–5…+10 VDC (referenced to GND)
Input resistance	100 kΩ (differential) 50 kΩ (referenced to GND)
A/D converter	12-bit
Resolution	5.07 mV
Bandwidth	10 kHz

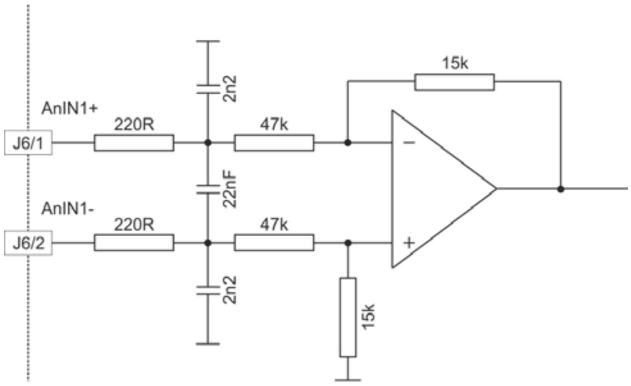


Figure 3-16 AnIN1 Circuit (analogously valid also for AnIN2)

3.3.6.2 Analog Outputs 1 and 2

Output voltage	–4…+4 VDC
D/A converter	12-bit
Resolution	2.30 mV
Refresh rate	AnOUT1: 26.8 kHz AnOUT2: 5.4 kHz
Analog bandwidth of output amplifier	20 kHz
Max. capacitive load	10 nF
Max. output current	1 mA

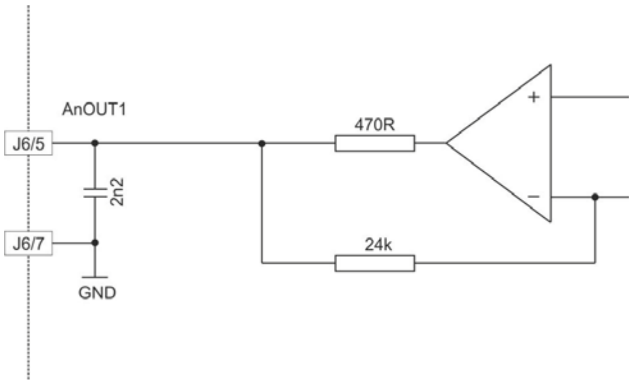


Figure 3-17 AnOUT1 Circuit (analogously valid also for AnOUT2)

3.3.7 USB (J7)

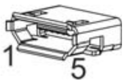


Figure 3-18 USB Socket J7

Note
Column “Head B” (➔Table 3-20) refers to USB terminals of your PC.

J7 & Head A Pin	Head B Pin	Signal	Description
1	1	V_{BUS}	USB BUS supply voltage input +5 VDC
2	2	D–	USB Data– (twisted pair with Data+)
3	3	D+	USB Data+ (twisted pair with Data–)
4	–	ID	not connected
5	4	GND	USB ground

Table 3-20 USB Socket J7 – Pin Assignment & Cabling

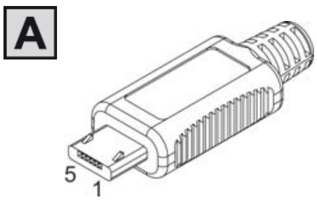
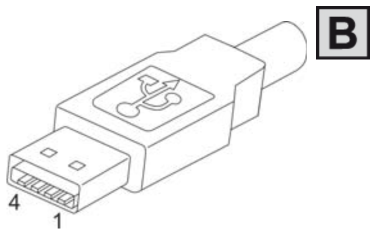
USB Type A - micro B Cable (403968)	
	
Cable cross-section	According to USB 2.0 specification
Length	1.5 m
Head A	USB Type “micro B”, male
Head B	USB Type “A”, male

Table 3-21 USB Type A - micro B Cable

USB Standard	2.0 (Full Speed)
Max. bit rate	12 Mbit/s
Max. bus supply voltage	+5.25 VDC
Typical input current	60 mA
Max. DC data input voltage	–0.5…+3.8 VDC

3.4 Potentiometers

POTENTIOMETERS P1 & P2

Adjustment angle	240°
Type	Linear

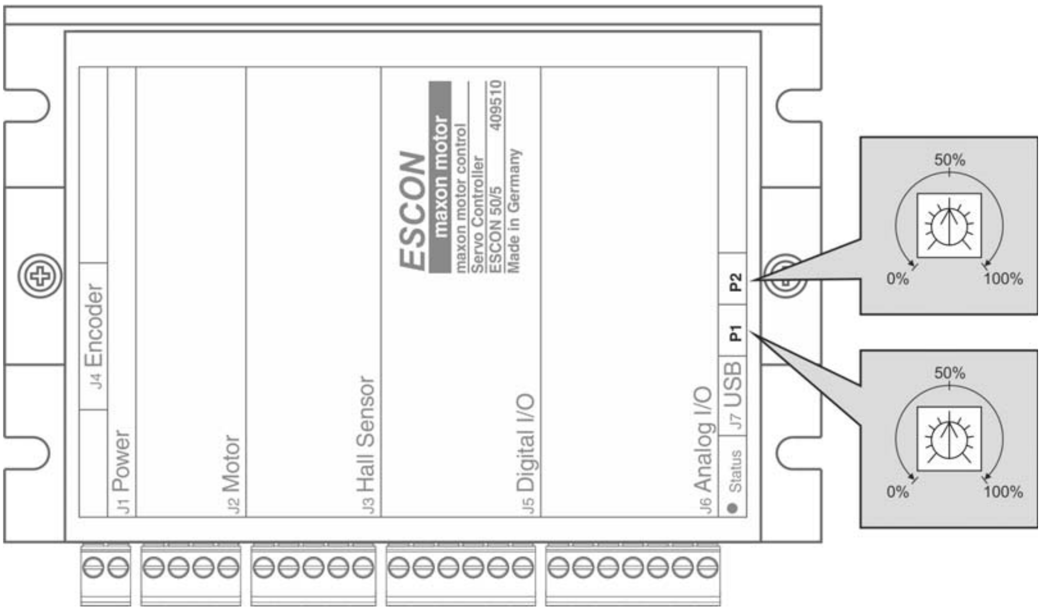


Figure 3-19 Potentiometers – Location & Adjustment Range

3.5 Status Indicators

Light-emitting diodes (LEDs) indicate the actual operating status (green) and possible errors (red).

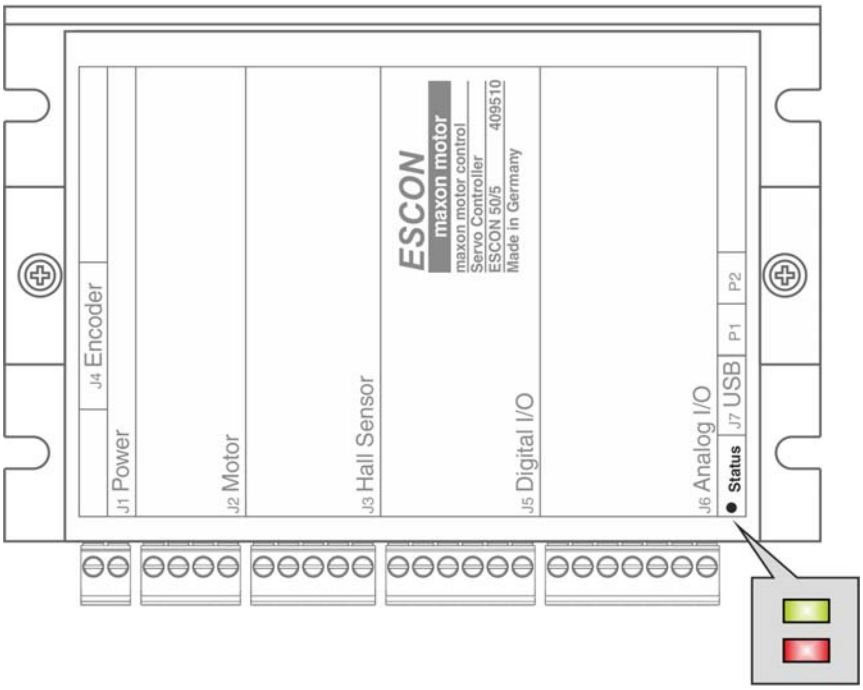


Figure 3-20 LEDs – Location

LED		Status / Error	
Green	**Red**		
off	off	INIT	
slow	off	DISABLE	
on	off	ENABLE	
2x	off	STOPPING; STOP STANDSTILL	
off	1x	ERROR	• +Vcc Overvoltage Error • +Vcc Undervoltage Error • +5 VDC Undervoltage Error
off	2x	ERROR	• Thermal Overload Error • Overcurrent Error • Power Stage Protection Error
off	3x	ERROR	• Encoder Cable Break Error • Encoder Polarity Error • DC Tacho Cable Break Error • DC Tacho Polarity Error
off	4x	ERROR	• PWM Set Value Input out of Range Error
off	5x	ERROR	• Hall Sensor Pattern Error • Hall Sensor Sequence Error • Hall Sensor Frequency too high Error
off	on	ERROR	• Auto Tuning Identification Error • Internal Software Error

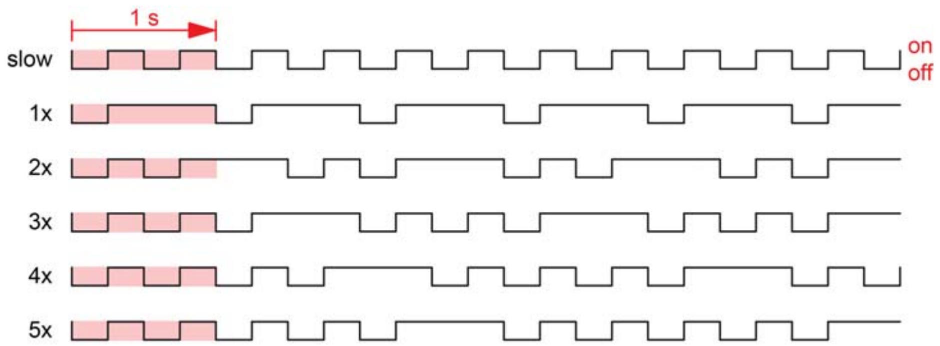


Table 3-22 LEDs – Interpretation of Condition

••page intentionally left blank••

4 Wiring

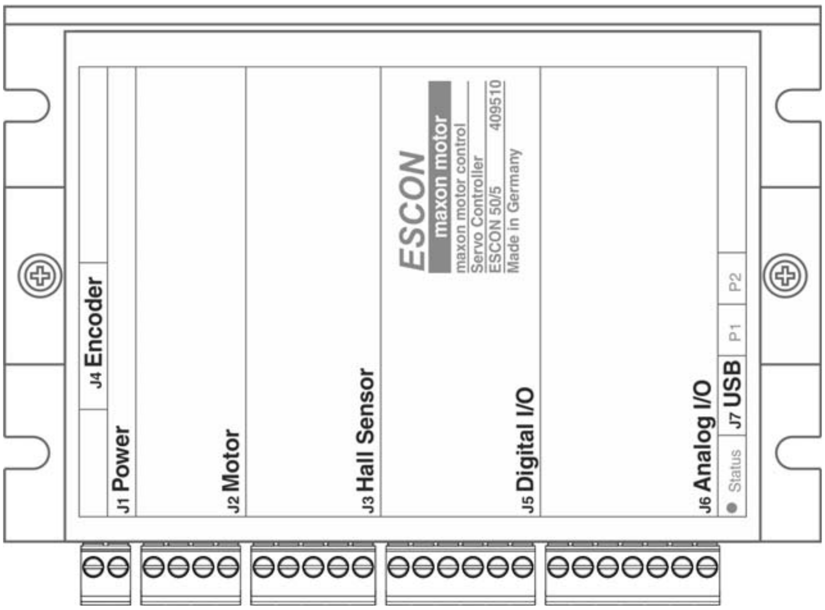


Figure 4-21 Interfaces – Designations and Location

Remark

The subsequent diagrams feature this sign:

- ⏚ *Ground safety earth connection (optional)*

4.1 DC Motors

MAXON DC MOTOR

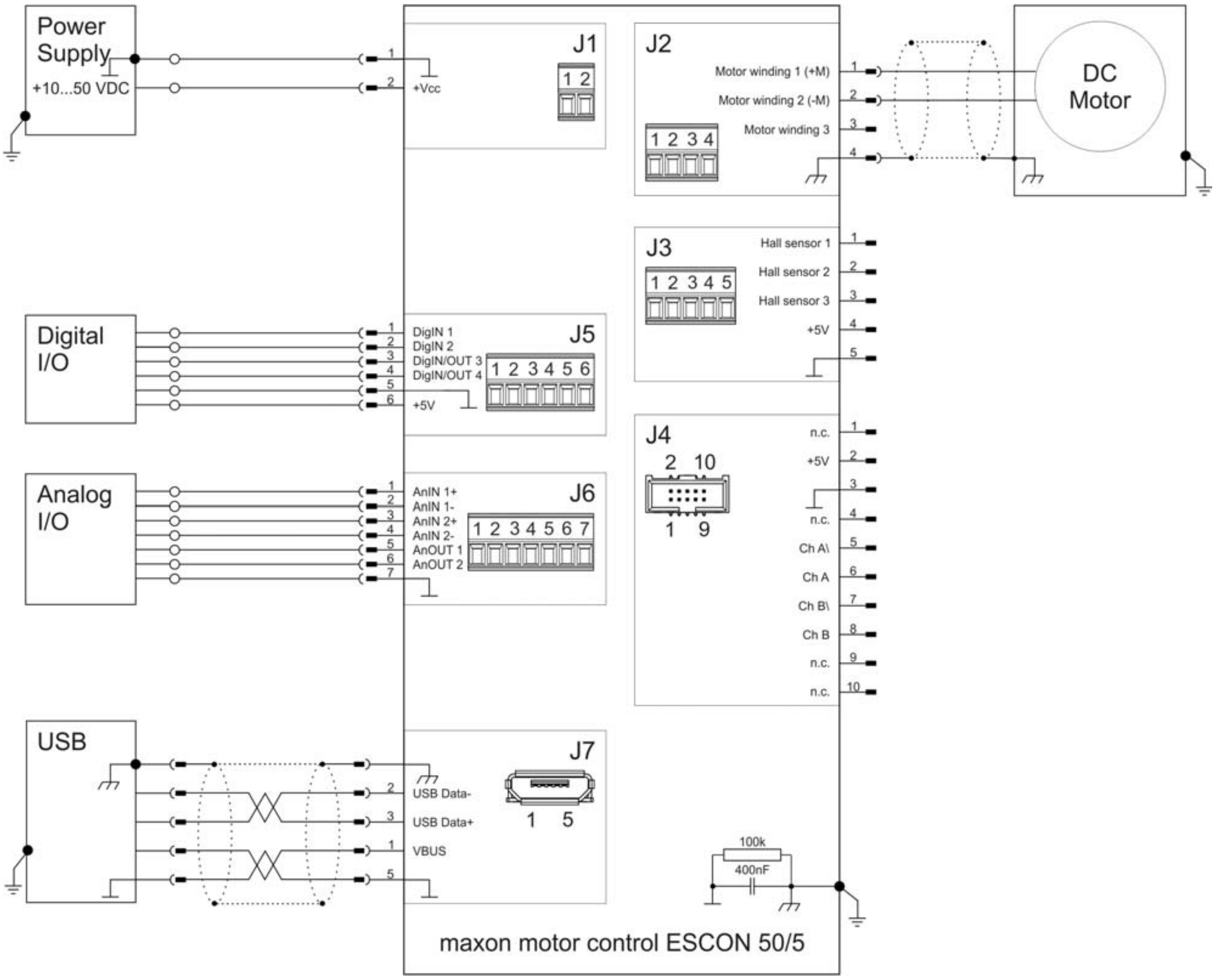


Figure 4-22 maxon DC motor (J2)

MAXON DC MOTOR WITH DC TACHO

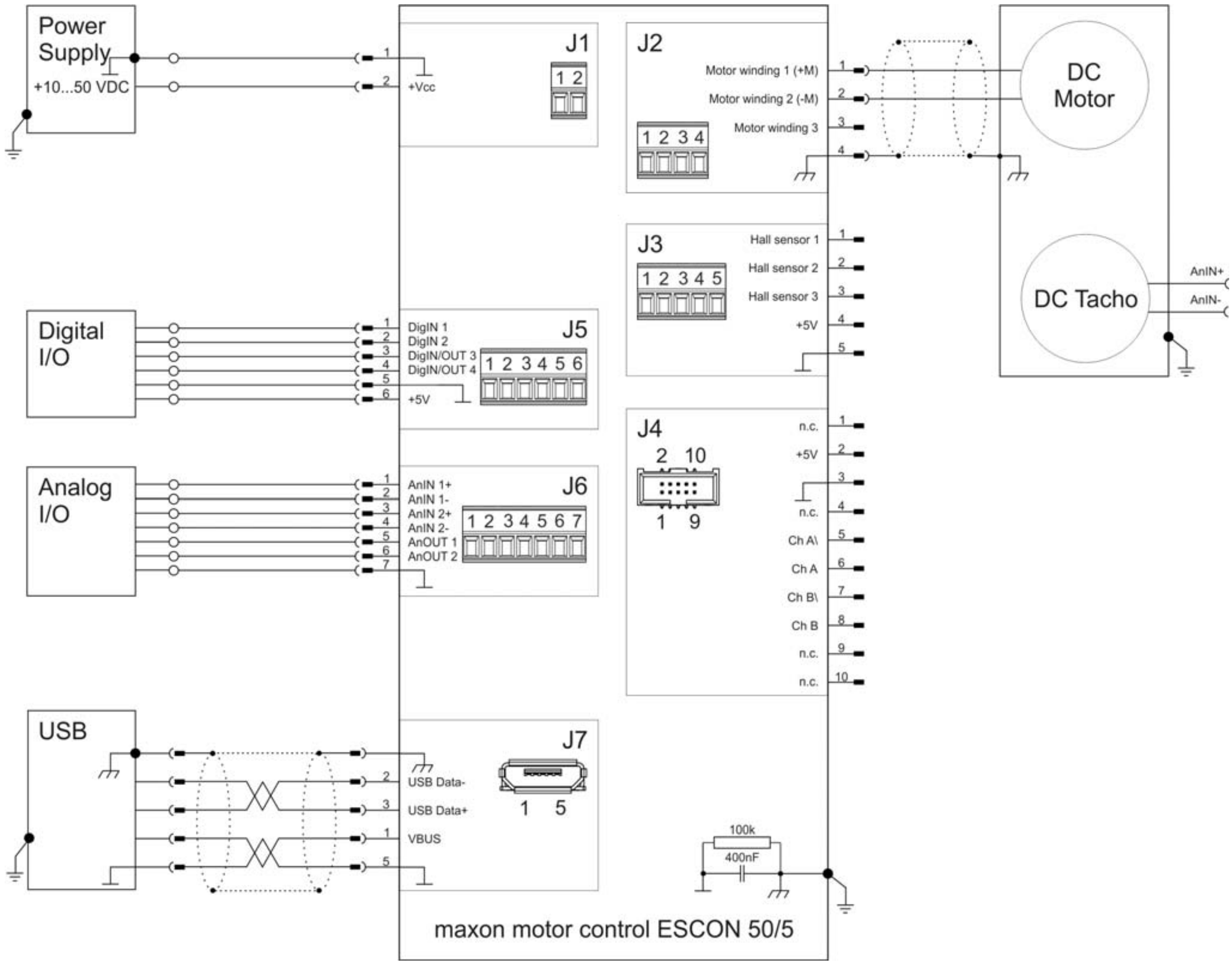


Figure 4-23 maxon DC motor with DC Tacho (J2)

MAXON DC MOTOR WITH ENCODER

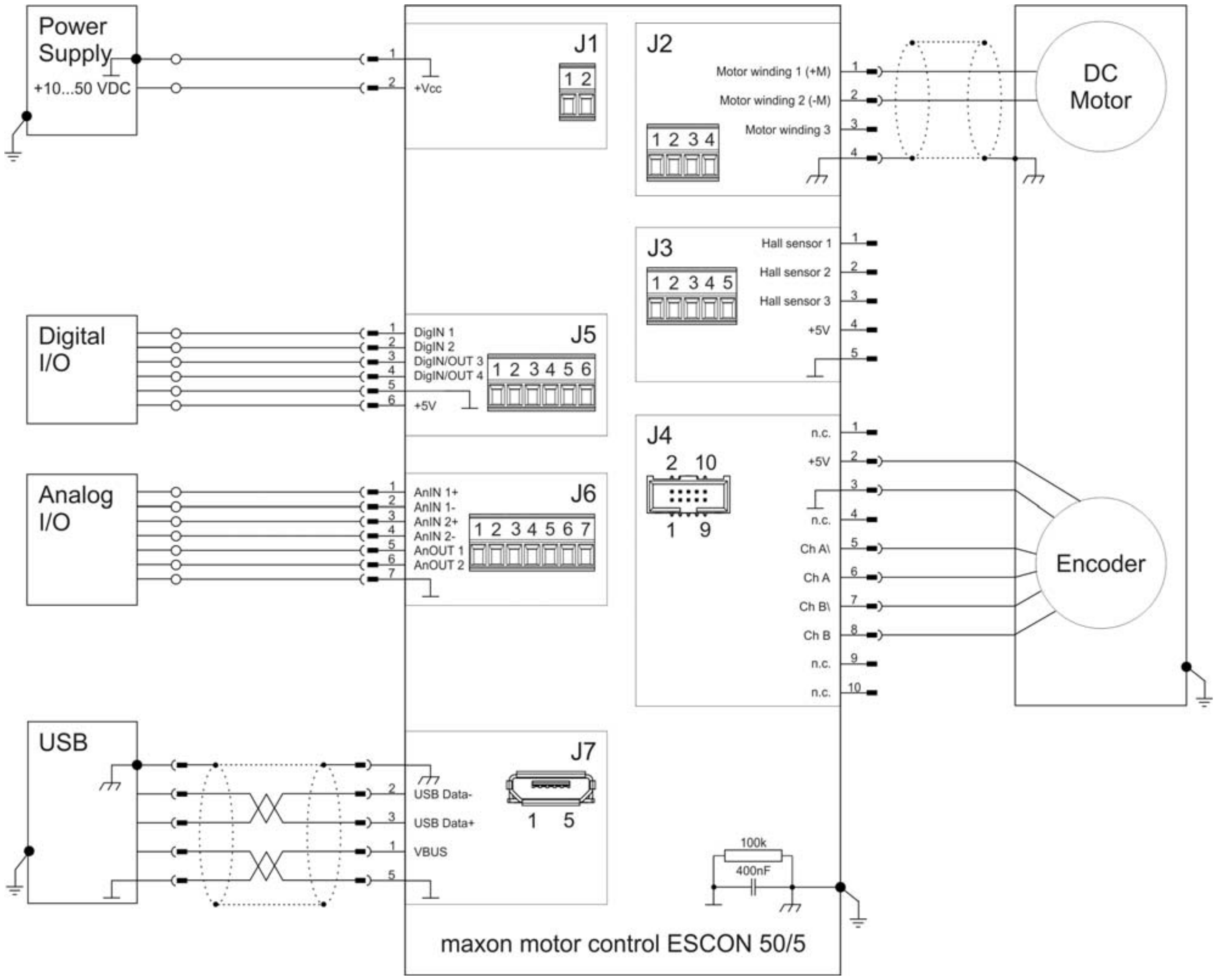


Figure 4-24 maxon DC motor with Encoder (J2 / J4)

4.2 EC Motors

MAXON EC MOTOR WITH HALL SENSORS

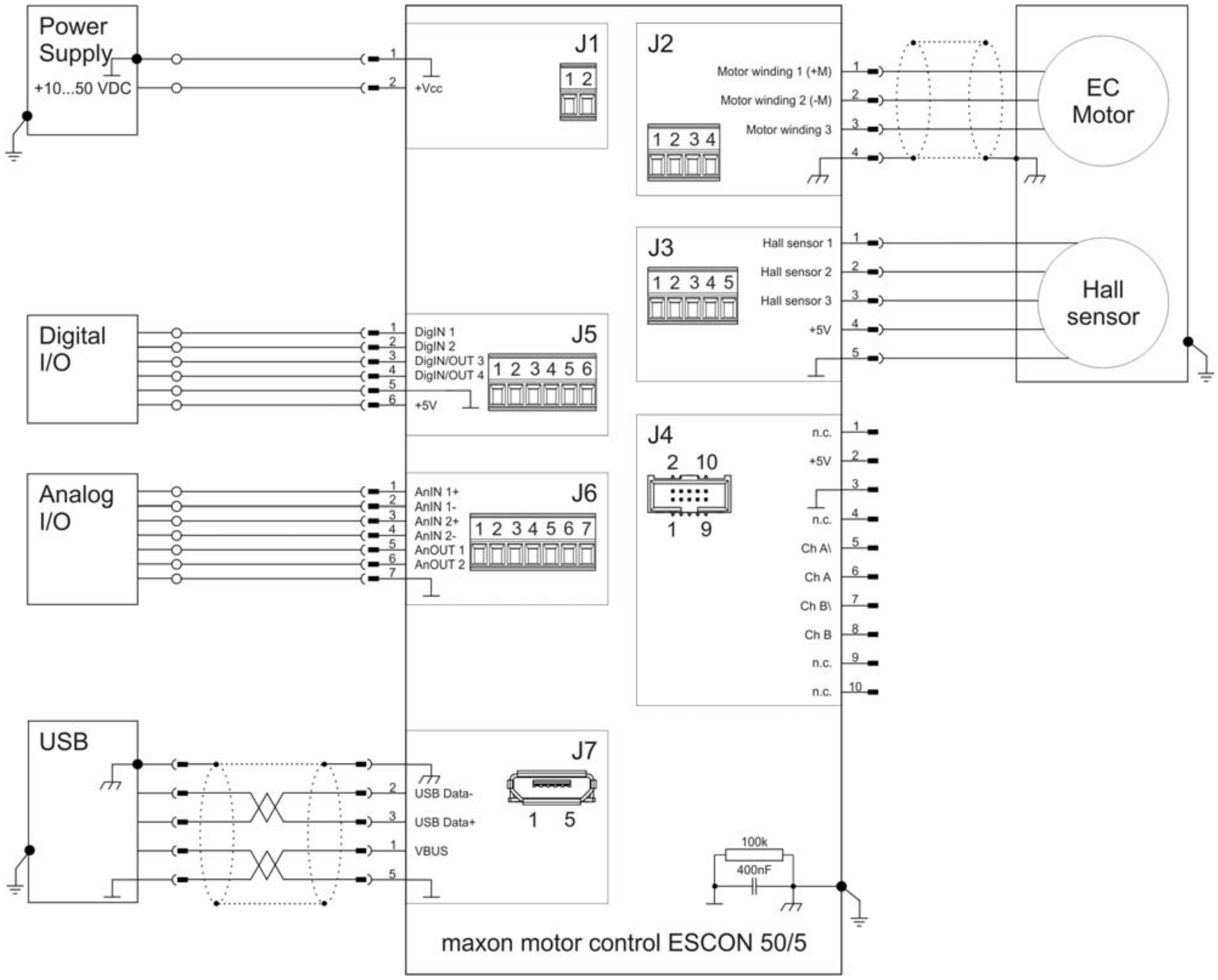


Figure 4-25 maxon EC motor with Hall Sensors (J2 / J3)

MAXON EC MOTOR WITH HALL SENSORS & ENCODER

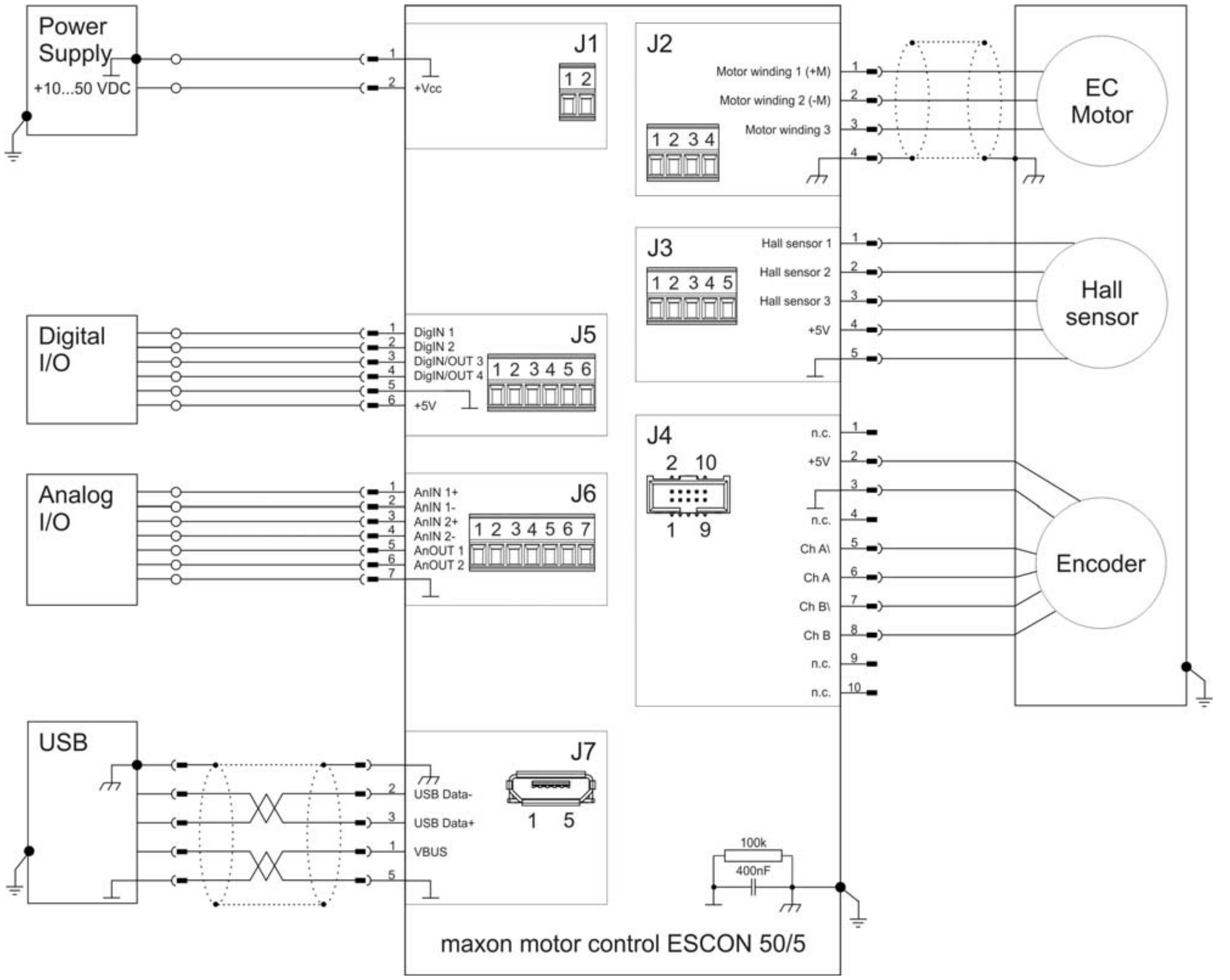


Figure 4-26 maxon EC motor with Hall Sensors & Encoder (J2 / J3 / J4)

5 Spare Parts

Order number	Description
425562	2 poles pluggable screw-type terminal block, pitch 3.5 mm, labeled 1…2
425563	4 poles pluggable screw-type terminal block, pitch 3.5 mm, labeled 1…4
425564	5 poles pluggable screw-type terminal block, pitch 3.5 mm, labeled 1…5
425565	6 poles pluggable screw-type terminal block, pitch 3.5 mm, labeled 1…6
425566	7 poles pluggable screw-type terminal block, pitch 3.5 mm, labeled 1…7

Table 5-23 Spare Parts List

••page intentionally left blank••

List of Figures

LIST OF TABLES

Index

maxon motor ag
Brünigstrasse 220
P.O.Box 263
CH-6072 Sachseln
Switzerland

Phone +41 41 666 15 00
Fax +41 41 666 16 50

www.maxonmotor.com

10.6 Appendix B - Simulink project guide

10.6.1 Start the project

To start the simulink project open the folder "eco_cars_control_system" in MATLAB. In this folder there is a file called "eco_cars_control_system.prj", dubbelclick on this and the project opens.

When the project is first started, a start-up script "Scripts/startup.m" is executed, this script sets up all needed parameters and imports relevant data to the workspace. It also adds needed paths and extends the library browser with "EcoCars control system blocks" and "EcoCars plant model blocks".

10.6.2 The main model

The main model is "main.slx", it is deployed to an Arduino mega 2560 in the back ECU of Elba. This model includes the interfaces to the real HW, the control system and a simple plant model. There is thee blocks that includes all drivers for the HW interface, the CAN controller block, the signals from real HW block and signals to real HW block. The CAN controller block handle all the can massages, it uses a stateflow chart to control witch message to be sent and when. Both the signal from and signals to real HW blocks uses bus signals as inputs and outputs. There are three main bus signals, driver commands, sensor signals and control signals.
It is easy to reroute the bus signals with switch blocks to use the plant model or the real system. The sensor bus can be taken from the plant model or the real HW and the driver commands bus can be the real signals from the driver or a test case that uses a signal generator.
Overrun detection is activated and if some task overuns (can not finisch before it should be run again) a led on the back ecu is turned on. If this happens the sample time has to be increased or the execution simplified.

10.6.3 Bus signals used in the main model

Driver commands
There only three driver commands in current configuration. The requested speed, the desired

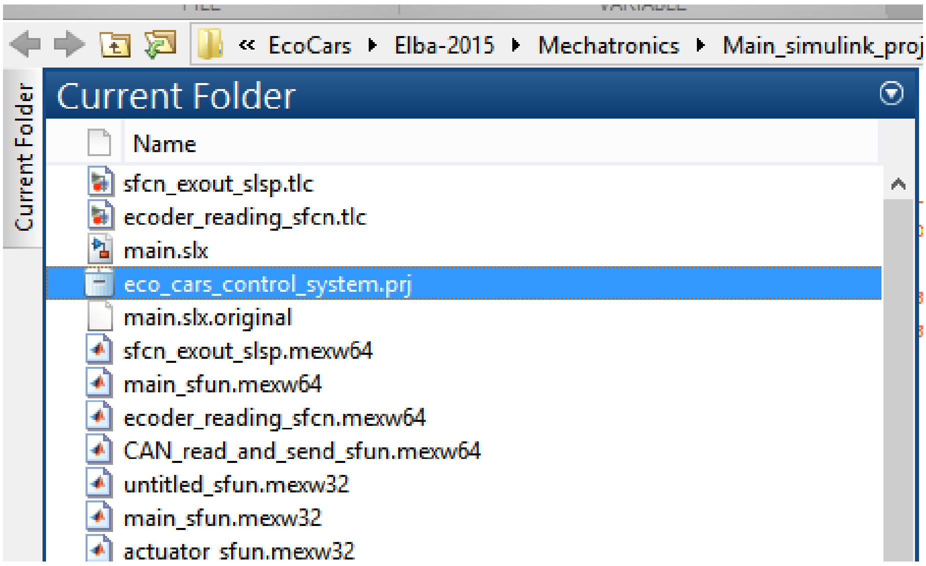


Figure 8: Open the simulink project

mode and the break pedal position. The requested speed can vary from -4 to 40 km/h in steps of 1 km/h. The mode is 0, 1, 2 and is used to run small motor (0), big motor (1) or ICE and regeneration (2). The break pedal position is 1 if the break pedal is pressed otherwise it is 0, this is used to set the speed to zero if the driver brakes.

Sensor signals

Includes the capacitor voltage and the rpm of the drive shaft. Capacitor voltage is the voltage of the capacitor multiplied by 100 (ex 4300 = 43V). The rmp of the drive shaft is shows the rpm of the shaft before the planetary gear, e. I. 10 times the rpm of the wheel.

Control signals

This bus includes all the actuation signals from the control system to the powertrain. Small motor enable/disable is 0 when the small motor driver is disabled and 1 when it is enabled. Small motor PWM is the duty cycle for the small motor driver, this should be between 10-90. Big motor enable enables the big motor when the signal is 1 and disables when the signal is 0. Big motor rpm sets the requested rpm for the big motor. Clutch big motor closes the clutch for the big motor when the signal is 1 and opens the clutch when the signal is 0. Same is for the ICE clutch signal. ICE on is a signal that enables the ignition of the ICE,

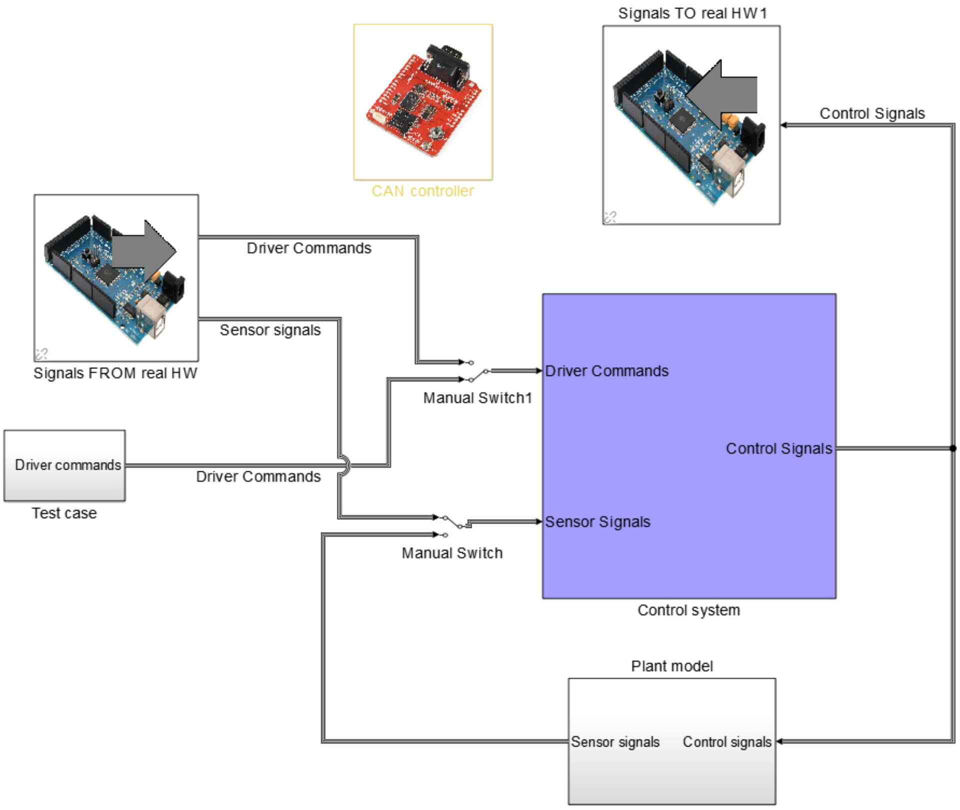


Figure 9: The main simulink model

when the signal is 1 the ignition is on and when the signal is 0 the ignition is of.

10.6.4 Deploying and running in external mode

When the system is deployed, the plant model should be out commented by select it and press ctrl-shift-x. The switch for the sensor signals should be shifted to read the real HW. Then the project can be deployed by pressing the deploy to hardware button in simulink. If test are made and the system can be simulated in external mode, then the simulation time should be set to inf and the simulation mode to external. When running external mode the driver commands can be taken from the real HW, a test case or just by modifying constant blocks.

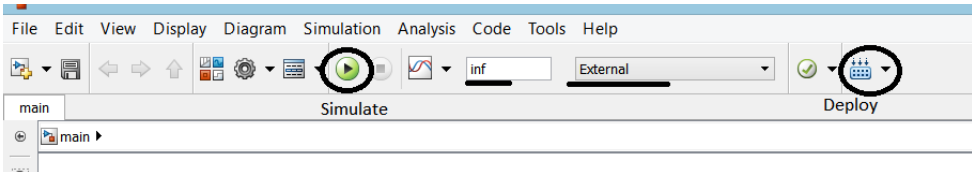


Figure 10: Deploy and external mode

10.6.5 Plant model

The plant model is a model of the car and has the same interface as the real HW. It takes the control signals as input and give the sensor values as output. But the model can be used for many more things as it has many internal parameters that can be used to verify test results. However all systems in the plant model needs to be identified and the models needs to be verified before performance tests can be done with the plant model. So far the plant model can only be trusted to use for function test e. g. check that the correct motors are turned on at the right speed and in the right drive mode.

10.6.6 Control system block

The task of the control system block is to read all sensor signals and driver commands and create the required control signals to the actuators such as electric motors clutch actuators and the ICE. At current state the control system get the drive mode from the driver through a driver command signal. According to the requested drive mode and other variables, such as voltage of the capacitor and speed of the car, different motors are enabled and clutches are opened and closed. A stateflow chart is used together with some PI controllers that are tuned with external mode. When the plant model is better the control can be improved using the model without the need of the car.

10.6.7 Custom source

To add functionality that is not supported by Simulink, for example to make additional drivers, new handwritten C function sometimes are needed, this code is included in the custom source. In the folder "Custom_src" are all files that are included in the custom source located. For the simulink model main.slx is the file main_custom_src.cpp the custom source file that is included during compilation. To include more functions they should be added ether directly to the main_custom_src.cpp file or in a separate file that will be included in main_custom_src.cpp. All the functions that later is called from simulink has to have extern "C" as a prefix.'

10.6.8 Add and change blocks in the library

One of the folders in the simulink project is called `Library`, in the folder are all blocks that has been tested and can be used in models such as the `main.slx` placed. If the blocks are added to `eco_cars_plant_model_blocks.slx` or `eco_cars_control_system_blocks.slx` the block will also be available from simulink library browser. To configure how the blocks appear in the library browser the file `slblocks.m` can be modified. Some blocks, especially driver blocks requires many files, it is then recommended to make a folder and put all related file in the folder. In that case the folder needs to be added to the path. Do this by a new `addpath()` function inside the startup script located in the `Script` folder.
All blocks added to the `Library` folder should be tested, when new functions and systems are added they should first be placed in the `Test` folder where the functions can be tested. When the block is moved to the library the test should be kept in the `Test` folder to use if changes are made later.

10.6.9 CAN controller block

The CAN controller blocks includes a state flow diagram that decides when to send witch can massages. This is needed because CANopen is used to communicate with the inverter. Reading can massages is with a fix interval.