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Development of a Test Bench for Verification of Electric Controls for Offshore Winch & Crane Applications

Lohr am Main, Germany
2017

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Relatório submetido à Universidade Federal de Santa Catarina como requisito para a aprovação na disciplina **DAS 5511: Projeto de Fim de Curso** do curso de Graduação em Engenharia de Controle e Automação.
Orientador: Prof. Marcelo Stemmer

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Esta monografia foi julgada no contexto da disciplina DAS5511: Projeto de Fim de Curso e aprovada na sua forma final pelo Curso de Engenharia de Controle e Automação.

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RESUMO

O trabalho de conclusão de curso descrito neste documento foi realizado na sede da empresa Bosch Rexroth AG, em Lohr am Main, Alemanha. Pertencente ao grupo Robert Bosch GmbH, ela foca em sistemas de acionamento e controle elétrico, hidráulico e mecânico tanto em máquinas móveis como industriais. O departamento responsável por acolher este projeto se chama Marine & Offshore. Nele são gerenciados tanto projetos submarinos quanto voltados à superfície marítima.

Nos últimos anos, grandes projetos para controle de guinchos de navios têm surgido, os quais envolvem controle ativo de compensação de ondulações provocadas por ondas (AHC). Como isso envolve guinchos montados em grandes navios capazes de erguer centenas de toneladas, o maquinário é extraordinariamente caro, e consequentemente o teste de controles e comissionamento em campo também é custoso. Por isso, a fim de possuir um ambiente de testes com condições reais, a construção de uma bancada de testes na fábrica para simular os equipamentos se tornou necessária. A sua construção fora começada há alguns anos utilizando um sistema de testes para guinchos usados na automação de teatros. Porém, durante o início deste projeto, seu progresso se encontrava estagnado.

Este trabalho foi responsável por retomar o desenvolvimento da bancada de testes para guinchos offshore, atualizando os objetivos com os desejos e capacidades atuais dos stakeholders envolvidos. A primeira etapa foi identificar os componentes já instalados ou em estoque e as funcionalidades já programadas. Posteriormente, a transcrição dos objetivos dos stakeholders para requerimentos de sistema formou uma documentação técnica útil para a sucessão do projeto. Neste processo, foram analisados os aspectos estruturais, hidráulicos e elétricos da bancada de testes. A comparação entre os requerimentos com a situação atual deu origem ao design de uma nova arquitetura de sistema, especificando os controles elétricos e suas conexões. O trabalho termina com a implementação da nova arquitetura de sistema e com a programação das funcionalidades nos controladores pertencentes à bancada de testes.

Palavras-chave: Requirements Engineering. Active Heave Compensation. Offshore. Crane. Winch. Test Bench.

ABSTRACT

The project described in this document was carried out at the headquarters of Bosch Rexroth AG in Lohr am Main, Germany. Belonging to the Robert Bosch GmbH group, it focuses on electric, hydraulic and mechanical drive and control systems in both mobile and industrial machines. The department responsible for hosting this project is called Marine & Offshore, and in it both underwater and sea surface projects are managed.

In recent years, large projects aimed on the control of winches installed on ships have emerged, which for instance involve active heave compensation (AHC) control techniques. As this covers winches mounted on large vessels capable of lifting hundreds of tons, the machinery is extraordinarily expensive, and consequently so is the testing of controls and commissioning in the field. Therefore, in order to have a testing environment with real conditions, the construction of a test bench in the factory to simulate the equipment became necessary. Its construction has begun some years ago using a test system for winches used in theater automation. However, during the beginning of this project, its progress was stalled.

This work was responsible for resuming the development of the test bench for offshore winches, updating the objectives with the current desires and capacities of the stakeholders involved. The first step was to identify the components already installed or in stock and the features already programmed. Subsequently, the transcription of stakeholder objectives for system requirements formed a useful technical documentation for the succession of the project. This process involved the analysis of the structural, hydraulic and electric aspects of the test bench. The comparison of requirements with the current situation gave rise to the design of a new system architecture, specifying the electrical controls and their connections. This work ends with the implementation of the new system architecture and programming of functionalities in the controllers belonging to the test bench.

Key-words: Requirements Engineering. Active Heave Compensation. Offshore. Crane. Winch. Test Bench.

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TERMS AND ABBREVIATIONS

AHC	Active Heave Compensation
CAN	Controller Area Network
CPU	Central Processing Unit
EAHC	Electric Active Heave Compensation
EMC	Emergency
E-Button	Emergency button
HMI	Human Machine Interface
HNC	Hydraulic Numeric Control
HPU	Hydraulic Power Unit
I/O	Input/Output
LOP	Local Operating Panel
MCC	Motion Control Cabinet
MLC	Motion Logic Control
MLD	Motion Logic Drive
MOPS	Manual Overload Protection Mode
MRU	Motion Reference Unit
PAHC	Primary rotary Active Heave Compensation
PC	Personal Computer
PHC	Passive Heave Compensation
PROFIBUS	Process Field Bus
QFD	Quality Function Deployment
RAHC	Secondary Rotary Active Heave Compensation
ROV	Remotely Operated Vehicle
SLC	SafeLogic Compact
SWS	SWivel angle Sensor
UFSC	Federal University of Santa Catarina
W3C	Winch & Crane Control Cabinet
XP	Extreme Programming

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1. INTRODUCTION

1.1. Contextualization

Although the world’s population increase is slowly decelerating, the actual annual rate of approximately 80 million additional people will lead to a total of 11.2 billion inhabitants by 2100, accounts the United Nations [1]. Inevitably, the hunger for resources, space and prestige also grows in parallel. As declared by the U.S. National Oceanic and Atmospheric Administration (NOAA), only five percent of the ocean have been explored so far. In addition to the fact that almost 71% of the world’s surface is covered by water, this is causing a big draft of investment to the offshore field.

Being the most important highway for international trade [2], the ocean is beneficial to several other human applications. As reported by the Organisation for Economic Co-operation and Development [3], offshore oil extraction currently accounts for 28 per cent of the global production. Beyond oil reserves, the available renewable energy sources in the oceans are capable of supplying the present world’s demand with only 0.1% of its potential [2]. This includes generation from offshore wind turbines, waves, tides, ocean currents, temperature gradients and salinity gradients.

Besides connecting countries by trading goods, the ocean bed is home of pipelines transporting oil and gas as well as cables of internet and energy, which are shown in Figure 1.

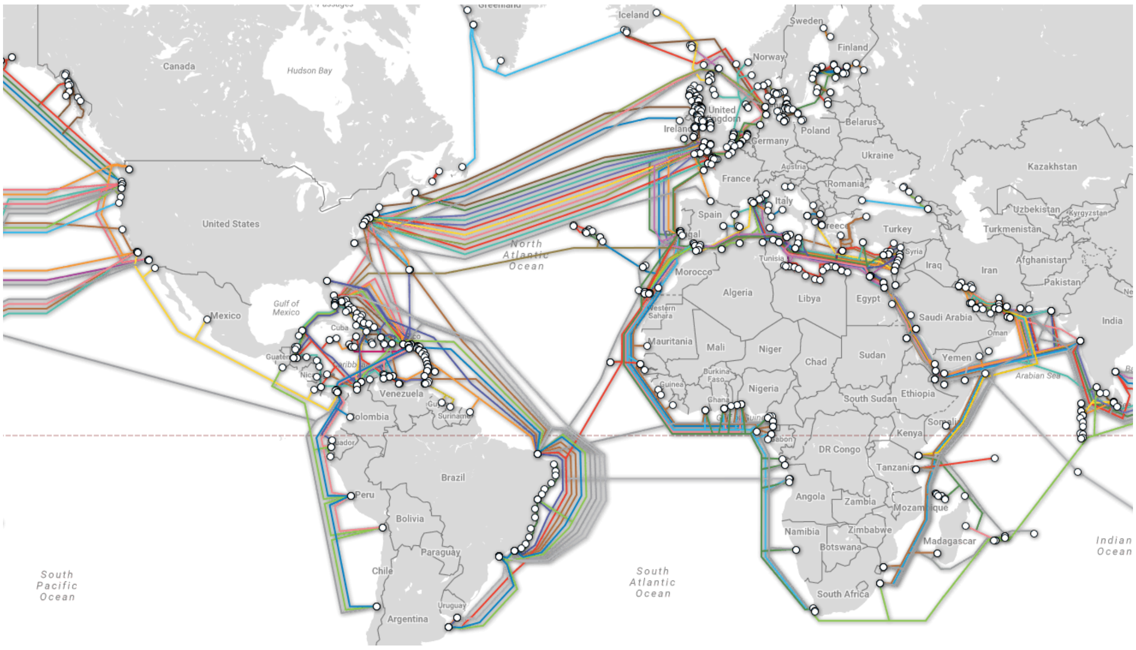

Figure 1: Illustration of existing submarine cables (extracted from [4]*)*

Due to the lack of knowledge about the subsea space, such as geographical features, mineral deposits or organic life, it is a place of research by human kind. Nowadays, this is performed more easily and efficiently mostly due to the advance of exploration technologies, such as more capable remotely operated underwater vehicles (ROV). An example of an ROV in operation is displayed in Figure 2.

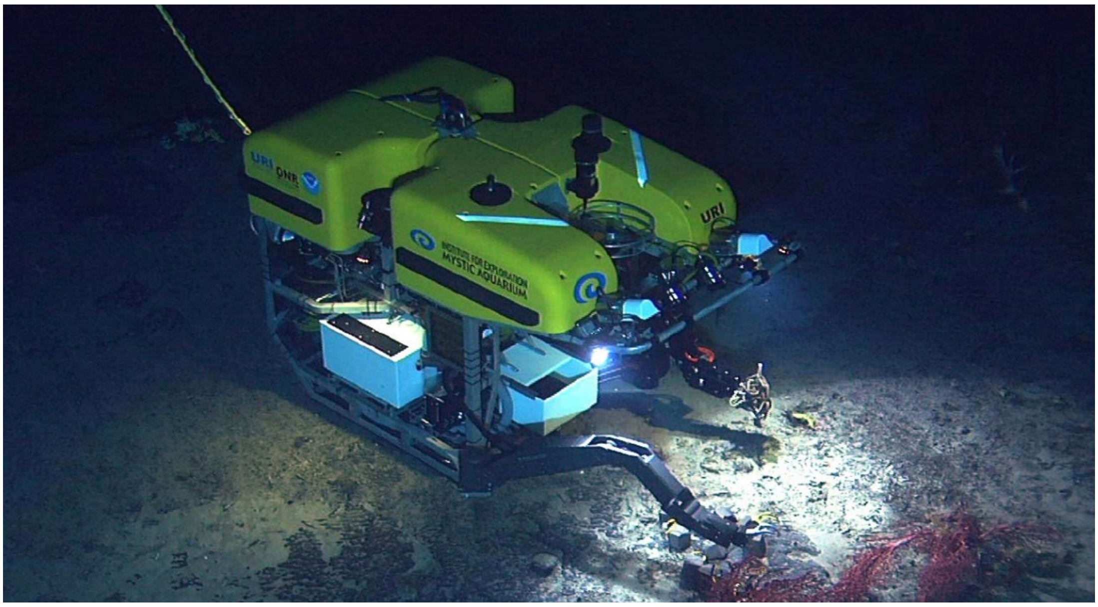

Figure 2: ROV Hercules built for the Institute for Exploration (extracted from [1])

1.1. Offshore cranes

Most of the offshore applications – including the previously cited – that carry out deployment or hoisting of both fixed and mobile structures have one device in common: a cable winch or similar system. This is often incorporated to a crane, which is responsible for the orientation of the cable in space, while the winch lower and hoist the load (indicated in Figure 3).

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[1] http://www.aquariumofpacific.org/news/story/explorers_gather_to_draft_first_u.s._ocean_exploration_plan

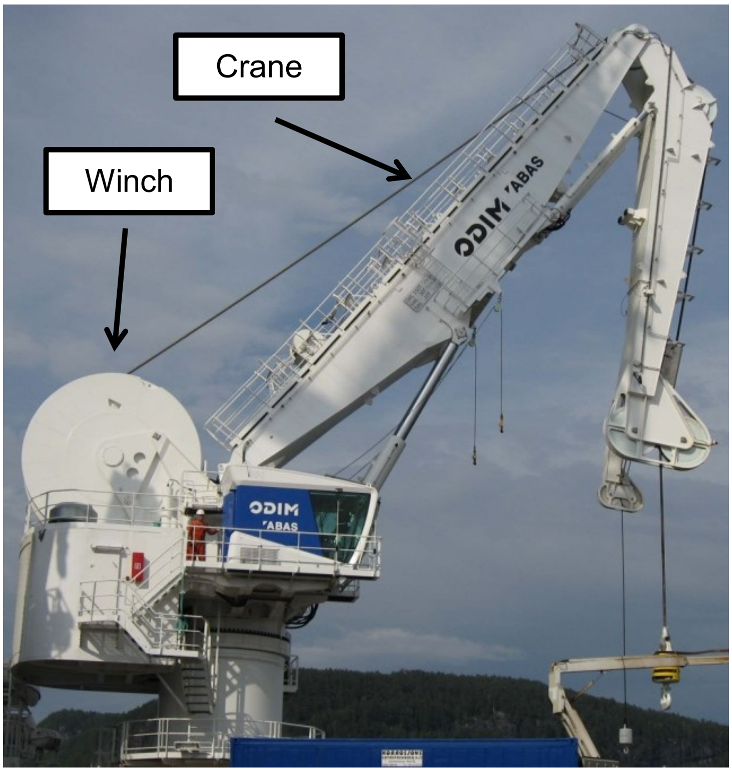

Figure 3: Description of a crane & winch system (source: ODIM Spectrum)

While one may think that this system is similar to cranes found on land, offshore activities encounter big challenges, as shown in Figure 4. Because vessels are normally floating on the surface of the water (jack-up rigs are exceptions), they also follow the sea undulations, whose amplitudes in normal conditions can reach up to a few meters. When working with either delicate or heavy loads, for example, such effect can cause damage to the attached load or even sink the ship. This is mostly because the water body where the load is located does not move vertically with the intensity of the heave, either causing severe stress on the cable or provoking slack. Especially when the suspended object is close to the seabed or any other surface that the vessel is independently moving from, this behavior is even more dangerous. Even if commanded by experienced operators, abrupt shocks can be easily experienced.

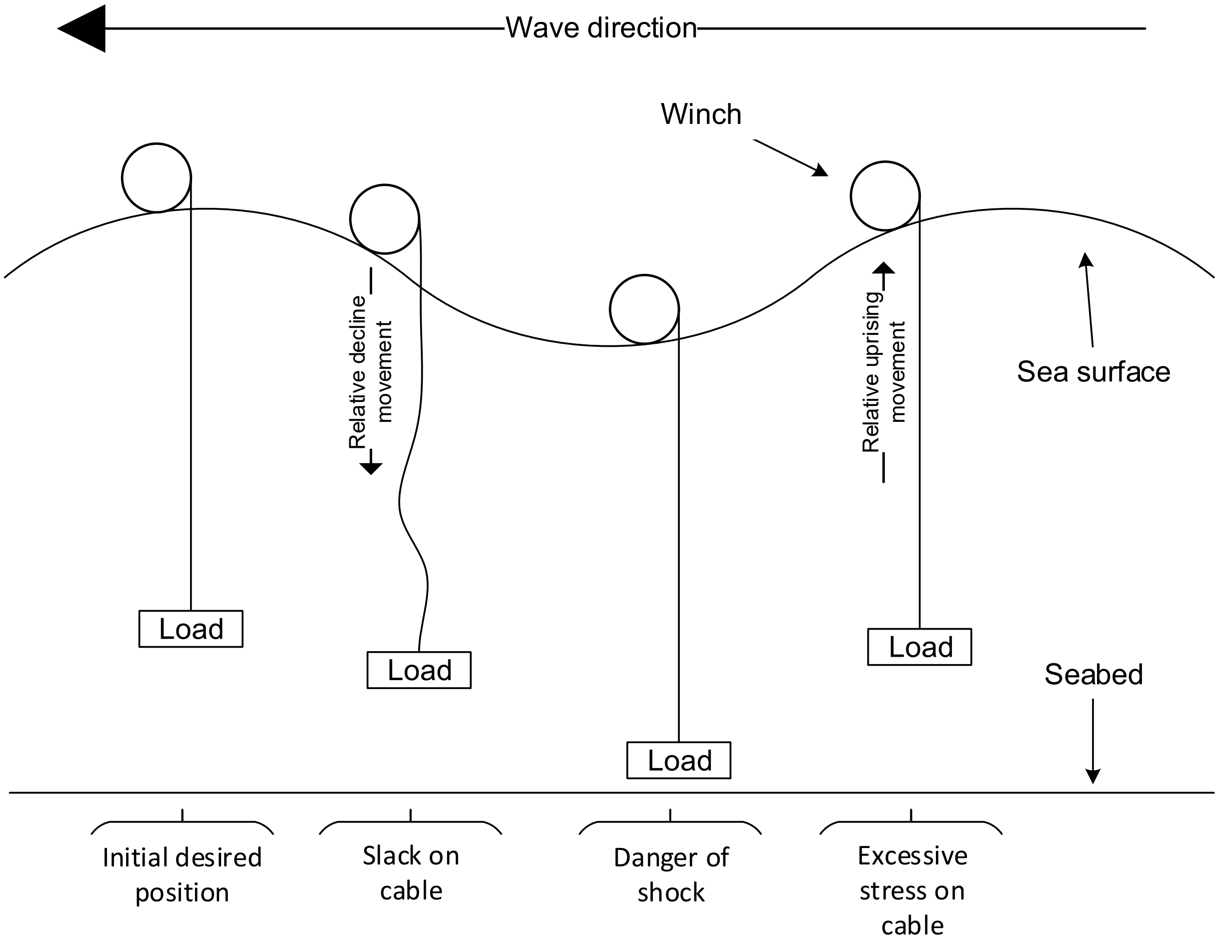

Figure 4: Demonstration of effects caused by heave during lift applications

1.2. Heave compensation

In order to reduce the effect of waves on drilling and lifting operations, heave compensation methods are employed [5]. Their purpose is to keep a suspended load with minimum undesired movement caused by the waves. This practice supports the following goals:

- Increase operational weather window, therefore reducing idle time;
- Enable positioning of delicate equipment;
- Safeguard equipment and operations

1.2.1. Passive Heave Compensation (PHC)

The simplest technique is called Passive Heave Compensation (PHC), and commonly utilizes a linear spring that can be located either across the cable or actuating on a tensioning pulley onboard the vessel. The last example is illustrated in

Figure 5, where the compensator cylinder works towards maintaining the cable tension as uniform as possible.

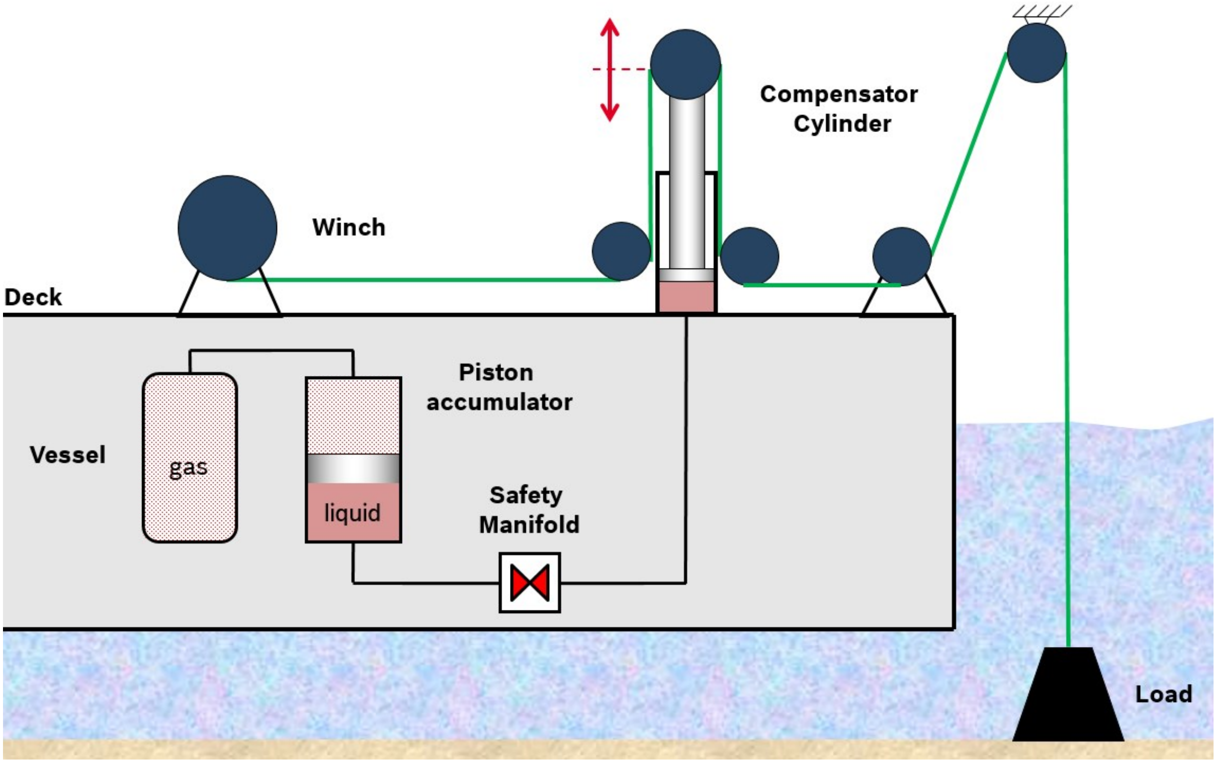

Figure 5: Working aspects of a common passive heave compensation system (source: Bosch Rexroth AG)

Since passive systems usually require no power supply for operation, they are beneficial when energy is scarce or when the operation can last over months, for example on suspended drillers. However, despite the improvement compared to non-compensated systems, it still does not provide the highest possible accuracy and range.

1.2.2. Active Heave Compensation (AHC)

Late technologies gave space to active heave compensation systems, where a controller tries to reject the heave movement when operating the winch. Although this technique requires power to function, it normally provides the best compensation performance.

The inputs of the motion controller are normally fulfilled by a motion reference unit (MRU), a device that has the capacity to detect the linear and angular movement of the ship in every direction. However, since the cable is usually very long in comparison to the ship's horizontal displacement, disturbances caused on the ship rather than in the z-axis (heave) are normally negligible. In fact, if the geometry of the crane and its relative position to the MRU are known, the vessel tridimensional agitation can be directly translated to the resulting vertical displacement of the cable, as indicated in Figure 6. This conversion is usually done inside the MRU using third-party algorithms and therefore not addressed in this document. The calculated motion is then applied to the winch drive in order to shift the cable in the opposite direction and maintain the hook stable.

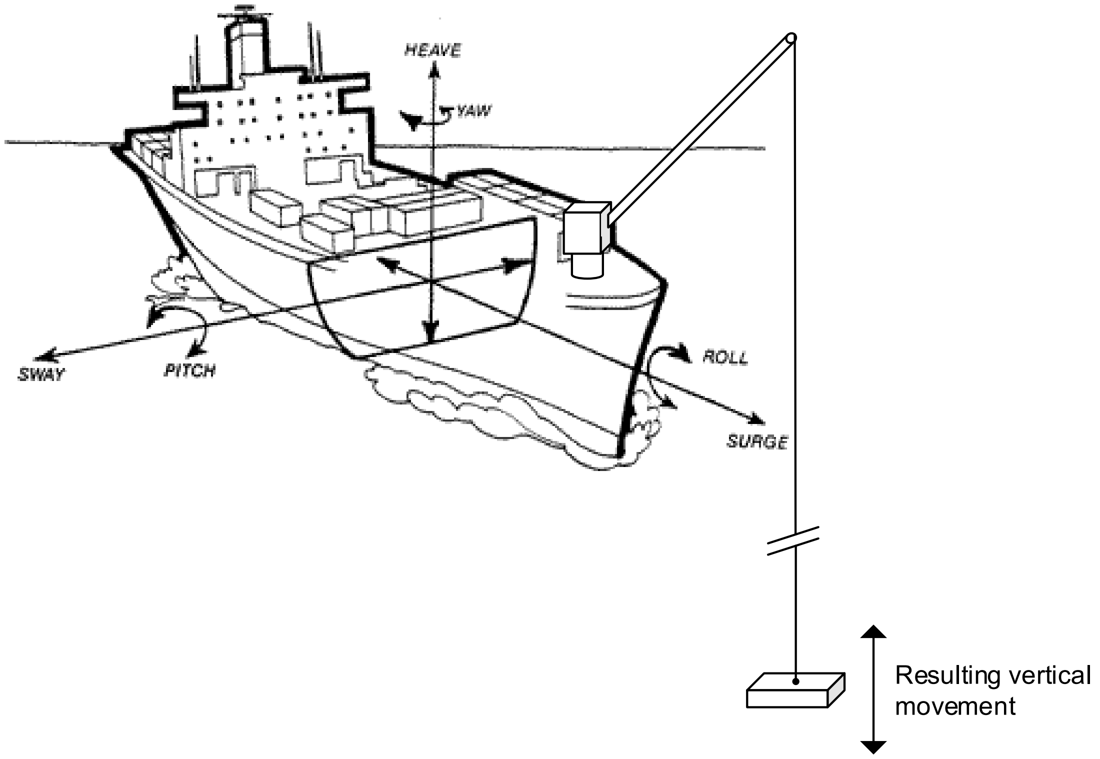

Figure 6: Degrees of freedom of a ship movement (adapted from [2])

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[2] http://www.surveyorslexicon.com/index.php?RefNum=1372

1.3. Target

The active heave compensation can be performed by different types of actuators, such as linear cylinders, electric winch or hydraulic winch. However, only the last two are currently focused by this work.

A new control solution for such systems based on modular elements was introduced by Bosch Rexroth in 2015. It supports the idea of having electric controls that are compact, easily customizable, and with simple installation. One important consequence of this concept is to allow designers to generate new systems more quickly and flexibly.

In order to save an expensive commissioning and testing processes on board of the ship, the modules shall be tested and adjusted by the hardware and software designers directly at Rexroth's laboratory before the delivery. This requires a test bench capable of replicating important environment conditions and requirements that are present in offshore applications. Located in one of Rexroth's facilities, an existing test bench for theater winches began to be adapted for this application before the start of this work. However, its progress and targets have lost clear track and its use was therefore not ready.

Given the previous inputs, the goal of this project is to restore the development of the test bench aimed at offshore winch and crane applications. This translates to the capacity of testing and pre-commissioning electric controls, testing software modules, and configuring communication to top level controllers.

The next chapter starts with a study of system management approaches and presents the addressed work packages as well as their flow throughout this document. The subsequent section brings the reader closer to the technical matters present in this work, presenting relevant control devices and techniques. The Chapters 4 to 6 are then responsible for demonstrating the engineering process from the inputs to the outcome of the development. Finally, the Chapter 7 encloses the final considerations about the fulfilled tasks and future perspectives.

2. METHODOLOGY

By the time of the start of this work, the first engineers that played an important role in the development of the test bench were already moved to other branches and projects across Germany. Since only adjacent members of development and management were left, the project carried neither a team with deep technical knowledge about it nor an organizational structure anymore. Unfortunately, a parcel of the previous progress was also not properly documented and discussed. Therefore, much information was either hidden under unorganized files and wires or simply lost. Although the previous working approach did not render results as expected, its analysis was useful to learn about the topics *Project Management* and *System Engineering*.

In order to run the project once again, a kick off meeting was organized. Colleagues who participated had either previous contact with the test bench or interest in working on the theme. This reunion allowed the creation of a new project structure, including the designated purpose of each team member. The scope defined for this work covers two major topics: management of all information in respect to the test bench, and technical assignments, mostly related to electric concerns. Both subjects are summed up, however, to the goal of making the test bench functional.

2.1. Project management approach: Agile Method

Before the technical development could take place, a project management method shall be established. The most traditional project management process, called “waterfall” or “the predictive process”, is characterized by long-term and detailed plans that must occur before any development work. The plans must contain detailed requirements regarding each phase of the whole project, as well as design documents and their analysis. One may think that this approach avoids misunderstandings, changes and late corrections the most, therefore resulting in less time and costs. However, naturally, rarely does a specification cover, or a stakeholder think of, every possible aspect. Moreover, even if they do so, it is a utopia to believe that they remain constant and viable until the finalization of the project. That means that there are always inevitable changes, independently of how well the initial planning was done. The resulting disadvantage with the “waterfall” method is that, for each small change, a lot of work is required, since it affects every development layer that has been previously labored. The progress through this traditional method is displayed in Figure 7. The vertical axis represents the certainty that the developed stage will remain without changes until the end of the project progress.

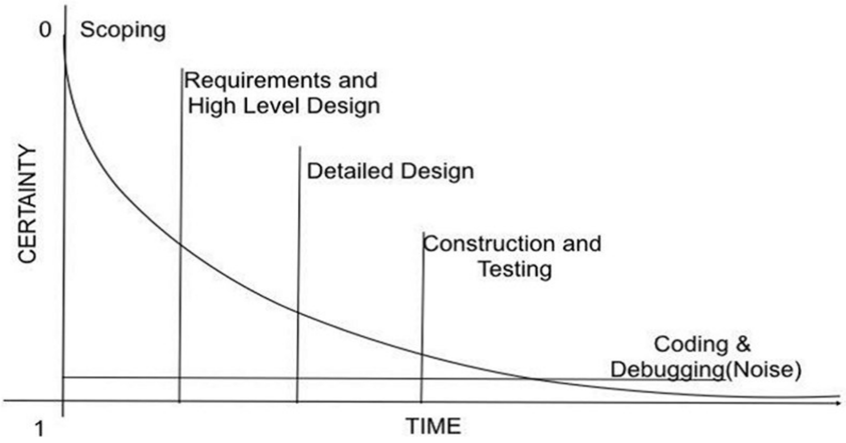


Figure 7: Progressive elaboration using the waterfall method (extracted from [6])

The “waterfall” method presents an exponential growth of costs related to late project changes, and this is what agile processes aim to attenuate, even if it implies in controversial approaches. The agile approach attenuates the amount of “upfront work” by starting to develop before every project detail is documented. In contrast to the traditional method, a highly iterative approach like XP has repeating, low-risk elaborations, as shown in Figure 8 [6].

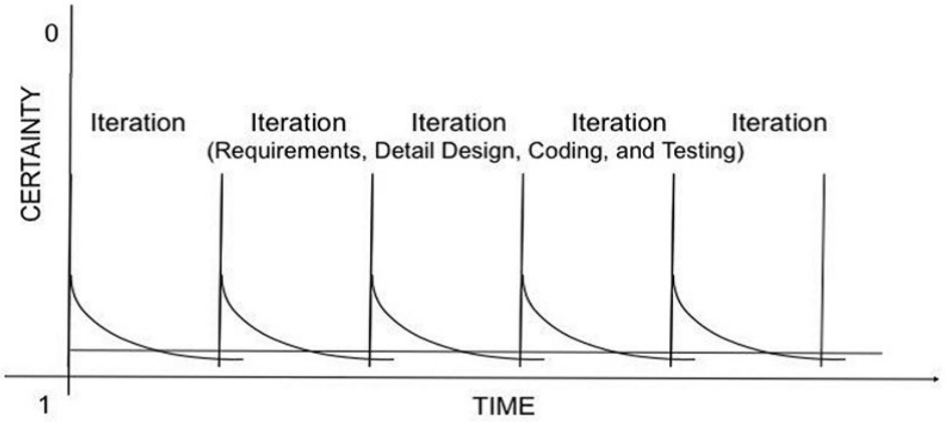


Figure 8: Progressive elaboration using the XP method (extracted from [6]*)*

Because of the small iteration sizes, the level of uncertainty is not too high. However, without the “up-front work”, most standard documents such as requirements specification are not written, and therefore this method is considered radical. Inside the range of the agile methods, it must be found the optimum balance between the “waterfall” method and the previous described XP. This spectrum can be illustrated by the Figure 9, where the horizontal line can be moved downward to represent a full traditional project, or moved upward to represent a fully iterative project, like XP.

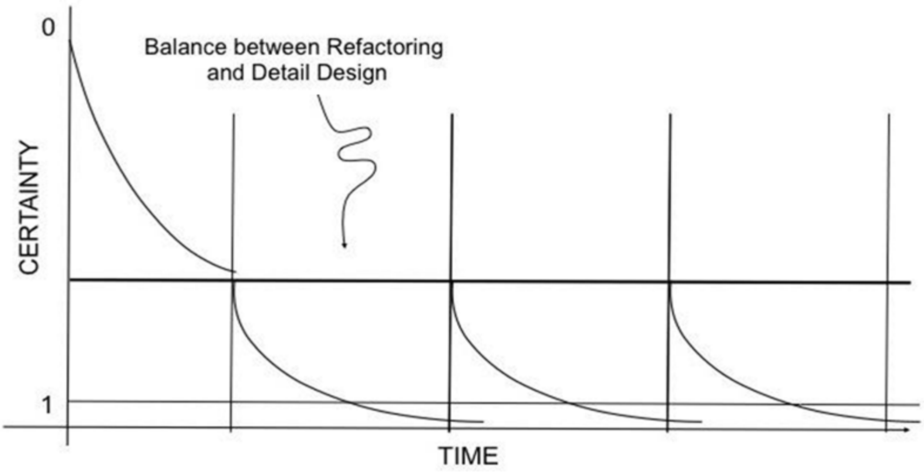


Figure 9: Progressive elaboration using a balanced agile method (extracted from [6]*)*

In the end, consumed effort is one of the most important factors when choosing the development method. Although this question varies slightly for each project, the Figure 10 roughly illustrates the available spectrum of different techniques and their relative effort, according to Alan Cline in “Agile Development in the Real World”.

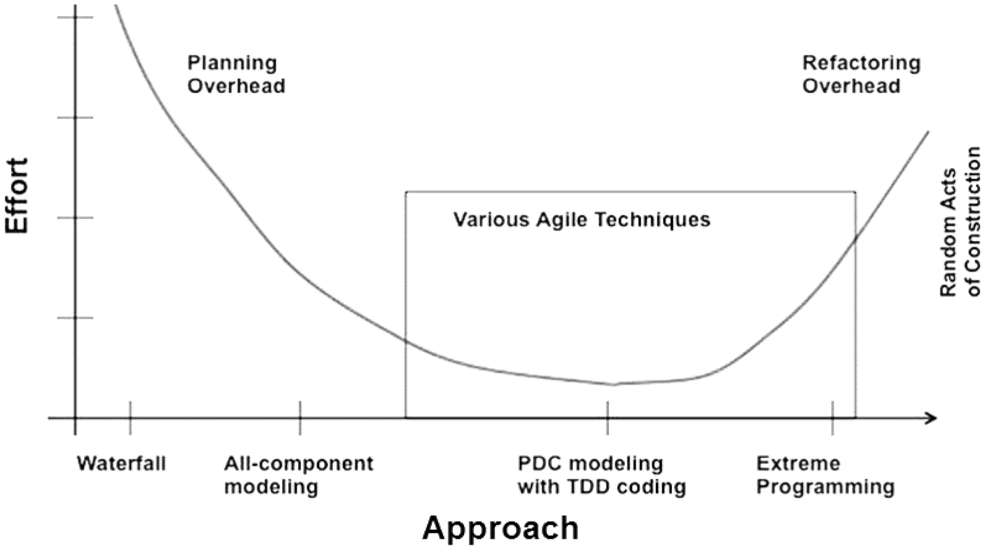


Figure 10: Effort vs. planning by project method (adapted from [6]*)*

The method adopted in the initial phases of development of the test bench resembles the XP practices, and the lack of documentation impacted on the relative unsuccessful result. Therefore, this work will be based on the principles of agile development, but including a significant foundation of project requirements. This aims have a guideline for the development and reduce random acts that do not bring useful content to the project growth.

2.2. Project development approach: Requirements Engineering

Despite one says that technology emerges to facilitate and solve the difficulties of mankind, it may cause the opposite effect on systems development. During every release of a new product, it is expected that they get better, faster and more helpful. To accomplish these ambitious goals, the industry plays a role in a race that gets each day more complex, especially with the introduction of software in the projects. One of the impacts of such a competition is the hurry to provide the merchandise to the market as fast as possible. However, taking 'time to market' as a goal is not enough: more adequate should be 'time to market with the right product'. Establishing the requirements enables us to agree on and visualize the 'right product'.

According to the surveys conducted by the Standish Group with IT executive managers [7], the Table 1 shows the most common reasons for project failures. These can be grouped in three main categories: Requirements, Management problems of resources and Politics. The first one, however, is by far the most recurrent, accounting 51.6% of the main causes.

Table 1: Reasons for project failures (adapted from [7])

Failure reason	**Percentage over total**	**Fall into requirements category**
Incomplete requirements	13.1%	Yes
Lack of user involvement	12.4%	Yes
Lack of resources	10.6%	
Unrealistic expectations	9.9%	Yes
Lack of executive support	9.3%	
Changing requirements/specifications	8.7%	Yes
Lack of planning	8.1%	
Did not need it any longer	7.5%	Yes
Lack of IT management	6.2%	
Others	14.2%	

The idea of dealing first with system requirements before looking at the procedures or solving approaches is not exclusive to this technique. It is also included in internal Bosch guidelines that are based on the QFD (Quality Function Deployment) method. Such project formula is described in Figure 11, where the correct entrance to problem resolution is pointed by the circulated arrow.

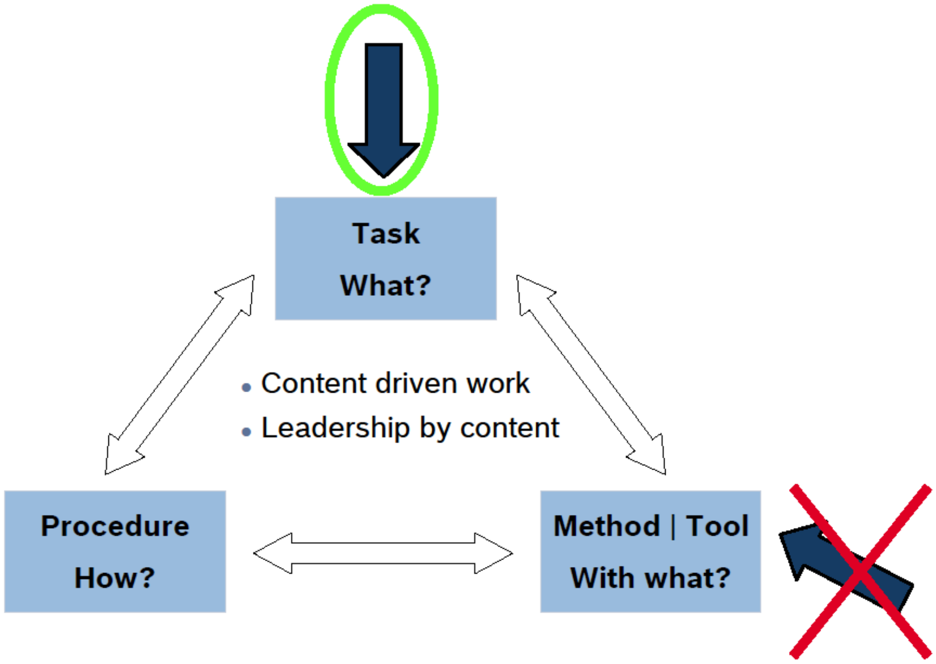


Figure 11: Problem approach supported by QFD Method (extracted from internal Bosch guideline)

2.2.1. Description of the methodology

Due to the importance of requirements engineering as a project foundation, it is important to understand it before the development takes place. This thematic surrounds the concept of systems, which definition is following:

> *"System is a collection of components – machine, software and human – which co-operate in an organised way to achieve some desired result – the requirements." (Extracted from [8])*

Another important concept is that of "systems of systems", where every system can be construed as being part of a larger, enclosing system. To understand the requirements of a system properly is to understand its enclosing and interfaced systems. For example, the ability of a car to move depends on the provided environment, such as the gravitational force provided by the earth. The same inter-connectedness also applies to the requirements structure, which makes it challenging to find a satisfactory scope for it.

It is interesting to consider the relationship between requirements and quality. There is no such thing as the "best product", since the term quality can mean different properties depending on the user exigency. When asked about the best automotive manufacturer, one can think about Bugatti due to its pioneering in high power automobiles, while other may think about Subaru because of its outstanding off-road performance and rally history. The truth is that quality means conformance to requirements, providing something that satisfies the customer. In other words, it describes the fulfilment of the needs of all the stakeholders. A stakeholder is defined as following:

> *"A stakeholder is an individual, group of people, organisation or other entity that has a direct or indirect interest (or stake) in a system." (Extracted from [8])*

A stakeholder's interest in a system may arise from using the system, benefiting from the system (in terms of revenue or other advantage), being disadvantaged by the system (in terms, for instance, of cost or potential harm), being responsible for the system, or otherwise being affected by it [8].

There is a common misconception that requirements is just a single phase work composed of a few lists which are carried out in the end of the product development. The requirements engineering, actually, has a vital role to play at every stage of development. Its architecture and lifecycle can be visualized in the V-Model of the Figure 12.

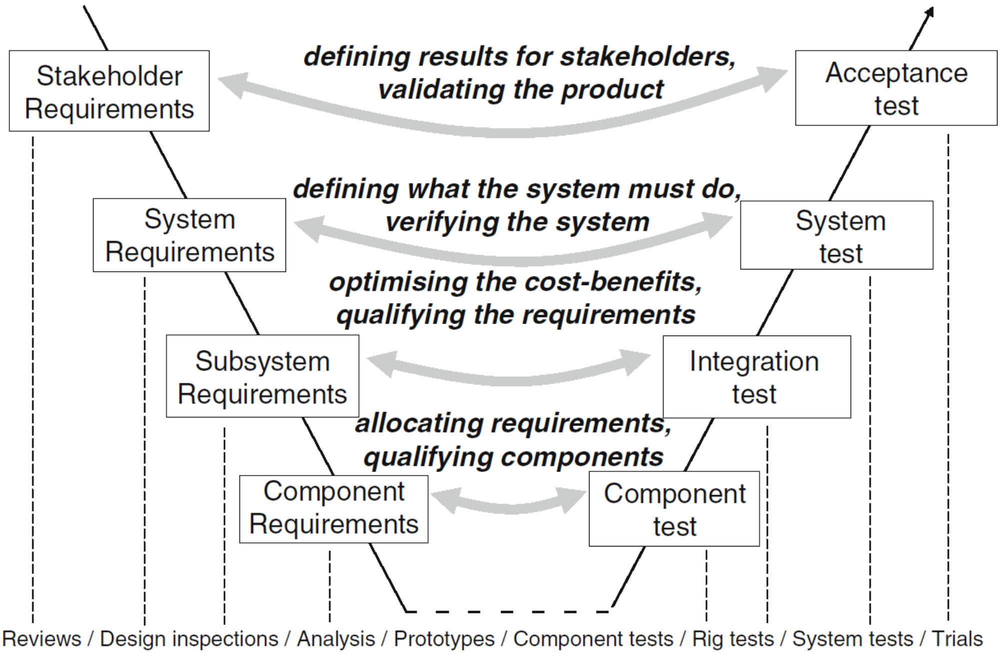


Figure 12: V-Model of the requirements layers (adapted from [8])

The use of a V-Model to represent the requirements provides two main characteristics to the requirements architecture. The first one is the relationship between requirements and testing, which affirms that everything needs to pass through a specific test until the system is fully validated. The hierarchy between layers is also inherited in this design. It affirms that every layer must address with what is above defined, without losses of information.

2.2.1.1. Requirements tracing

The act of transforming high-level requirements – objectives, goals, aims, aspirations, expectations, and needs – into low-level requirements is called tracing. This transformation can be translated into questions as placed in the Figure 13.

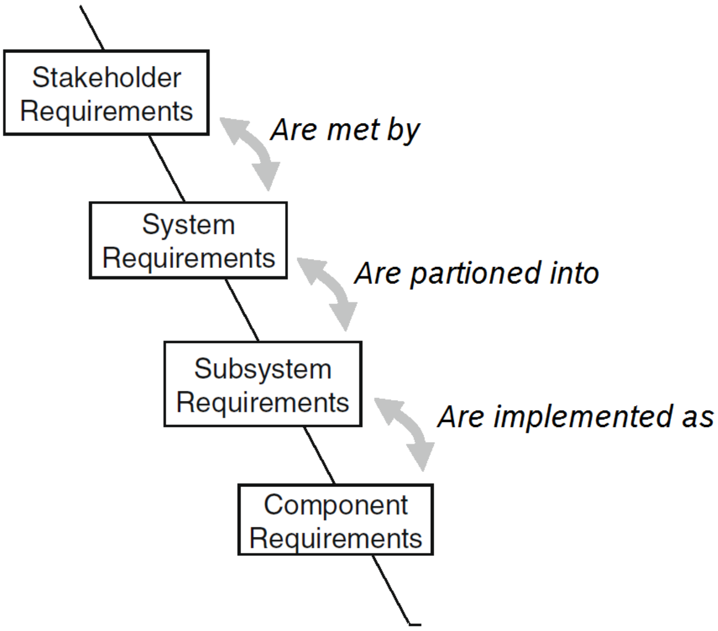


Figure 13: Steps of requirement tracing (adapted from [8])

Traceability relationships are usually many-to-many – that is, one lower-level requirement may be linked to several higher-level ones, and vice versa. One example of a useful feature that this architecture presents is the detection of elements that are potentially adding cost without benefit, in case they are not easily traced back.

2.2.1.2. Coverage analysis

The coverage property present in the Figure 14 affirms that all requirements do trace downwards to lower layers, and across to tests [8]. The absence of such a trace is an indication that the requirement will not be met or tested. It also provides a good measure of progress and integrity, indicating which higher-level requirement is successfully implemented and tested.

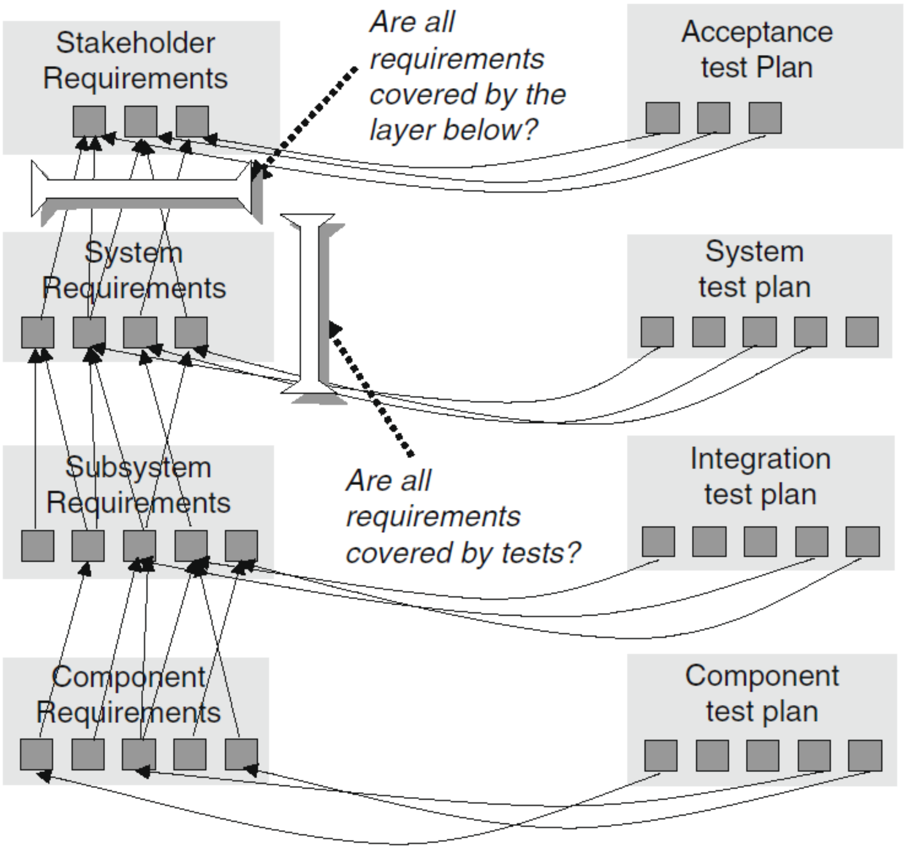


Figure 14: Coverage analysis (extracted from [8])

2.2.1.3. System modelling

Requirements management and system modelling are activities that should not be equated, but used for mutual support. A model is an abstraction of a system that deliberately focuses on some aspects of a system to the exclusion of others [8]. They assist the requirements engineer in the analysis of a particular level of details to achieve the following goals:

- Communicate with the stakeholders and improve mutual understanding of the system to be developed.
- Analyze the system to ascertain the presence of desired emergent properties (and the absence of undesirable ones).
- Determine how to satisfy the requirements by deriving new requirements at the layer below.

2.2.1.4. Understanding different layers purposes

In order to avoid inconsistencies, a clear distinction should be made between the problem and the solution domain (Figure 15). The initial stages of development, which are associated with the highest levels of system description, such as usage modelling and stakeholders requirements, belong exclusively to the problem domain. The subsequent layers, starting with system requirements, make up the solution domain.

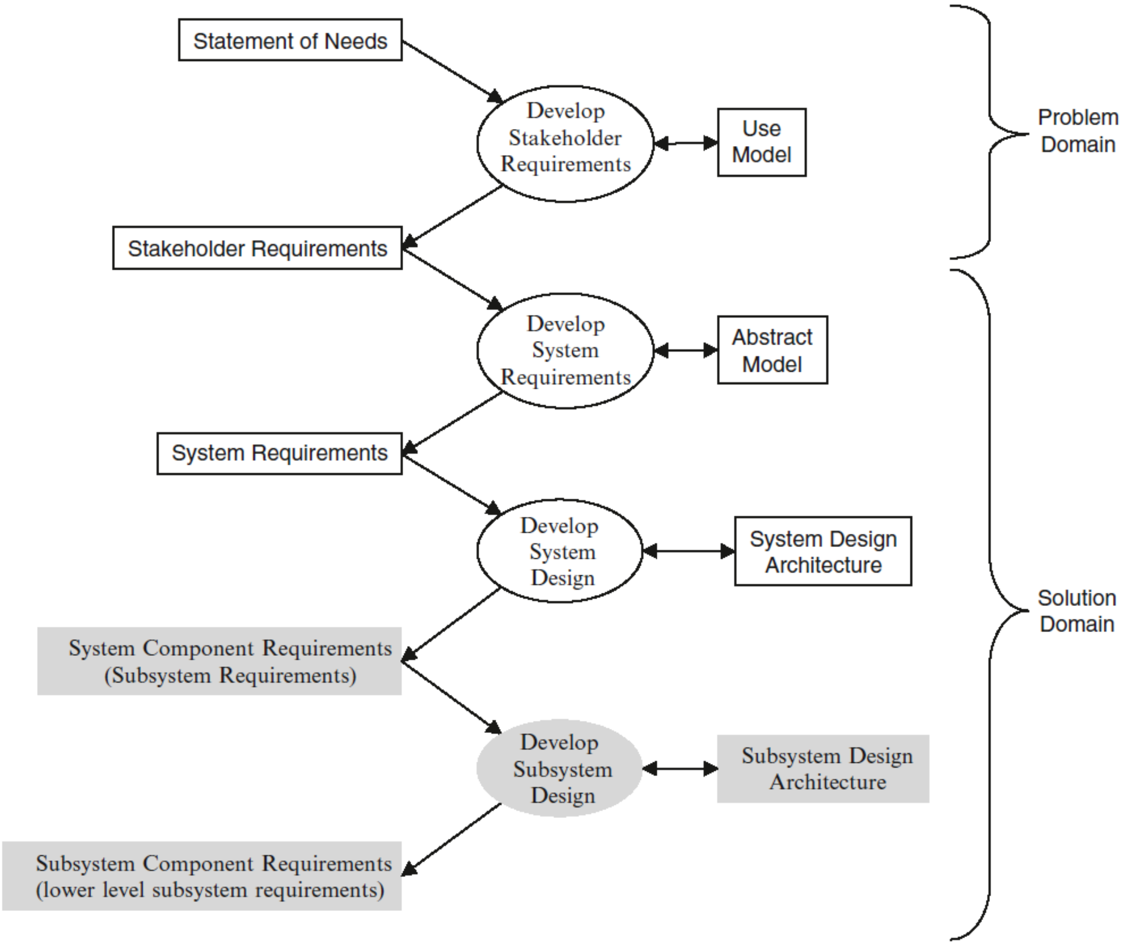


Figure 15: Problem and solution domains (extracted from [8])

According to the Table 2, due to the different nature of requirements through the layers, the responsible professional also changes accordingly. This is an important principle of architecture that assures the highest degree of freedom to the lower layers. Avoiding undesired solution bias and preconceived ideas, the designers are free to choose a solution to the stated problem within the correct scope.

Table 2: Problem and solution spaces [8]

Requirements layer	**Domain**	**View**	**Role**
Stakeholder requirements	Problem domain	Stakeholder's view	State ***what*** the stakeholders want to achieve through use of the system. Avoid reference to any particular solution.
System requirements	Solution domain	Analyst's view	State abstractly ***what*** the system will ***do*** to meet the stakeholder requirements. Avoid reference to any particular design.
Architectural design	Solution domain	Designer's view	State ***how*** the specific design will meet the system requirements.

2.3. Work flow

With foundation in the agile process previously described in chapter 2.1, this work covers the technical issues presented in Figure 16. This means that the developer does not need to finish one level entirely before moving forward to the next step. Instead, during the progress towards the last work package, small blocks of work should be addressed to each iteration. This way, work packages can be approached parallelly and recursively.

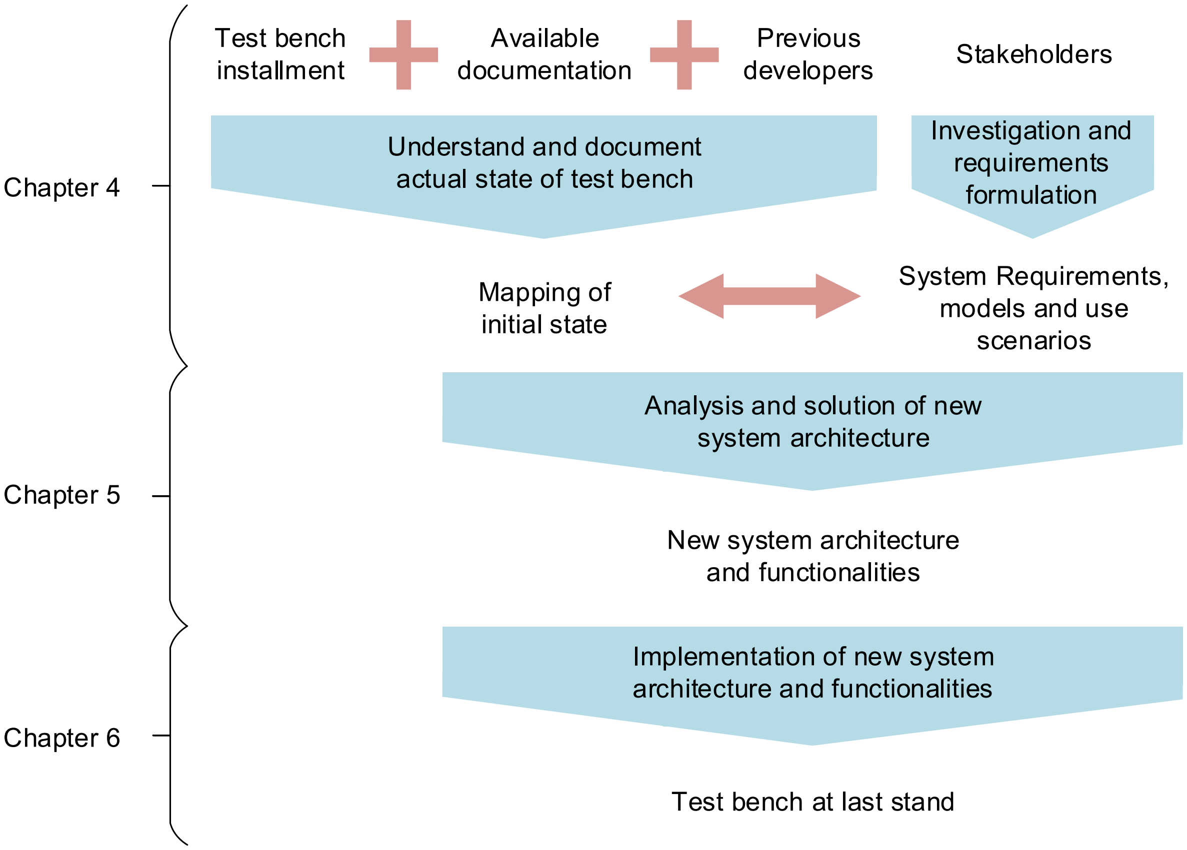


Figure 16: Work packages addressed in this thesis

The first stage of development, Chapter 4, consists of creating the two essential pillars that will sustain the succeeding compromises and solutions. After that, Chapter 5 employs the available material to design an architecture solution that satisfies the test bench requirements and capacity. The last development stage, Chapter 6, implements the design solution with the creation and application of new electric circuits, as well as the start of programming of expected software functionalities.

3. TECHNICAL BACKGROUND

In order to make the following chapters more understandable for the reader, this section is included to explain terms and concepts that are used throughout this document. It embraces specific electric controllers, hydraulic components, as well as control strategies that are handled in the context of AHC.

3.1. Electric controls

3.1.1. RC28-Box

Also called RC-Box (Figure 17), or even Hydrocontrol Box, it is a control cabinet that offers a cost effective solution for a large range of hydraulic applications due to its modular design.

Figure 17: The RC28-Box (Hydrocontrol Box) (source: Bosch Rexroth)

This cabinet accommodates a Bosch RC28-14/30 mobile controller, which is broadly used in the automotive industry due to its robust design and reliability. When installed in the box, the assembly supports the following features and interfaces [*9*]:

- Two frequency inputs suitable for low resolution incremental encoders;
- CANopen for communication with external controllers;
- Analog current inputs and one output;
- Analog voltage inputs and outputs;
- Digital inputs and outputs (24V).

3.1.2. Winch & Crane Control Cabinet (W3C)

The W3C is similar to the RC-Box, maintaining the same RC28-14/30 controller but with extra features such as a dedicated safety logic controller (SLC) and broader software capabilities. It replaces the RC-Box in future projects.

3.1.3. HNC100-SEK

The HNC100-SEK (Hydraulic Numeric Control for Secondary Control) (Figure 18) is suitable for closed-loop speed and torque control of axial piston units using secondary control. The following features are present in this controller [10]:

- Profibus DP or CANopen for the communication with PLC;
- Analog differential current inputs;
- Analog differential voltage inputs and outputs;
- Digital inputs and outputs (24V);
- Up to 2 incremental encoder inputs with monitoring function for the speed or rotary angle sensing;
- Two modules with monitoring function for inductive swivel angle sensors;
- Interface to SSI sensors.

Figure 18: HNC designed for four axis control (source: Bosch Rexroth)

3.1.4. Motion Logic Control (MLC)

The IndraMotion MLC (Figure 19) is a controller/PC-based solution for both motion and logic automation. A scalable hardware platform is adopted, allowing the support to the most common standardized communication interfaces, such as Sercos, PROFIBUS, Multi-Ethernet and CAN [11]. Provided insertion of additional I/O modules, the PC-rated CPU can interface with most of existing contemporary components.

Figure 19: Example of an IndraMotion MLC (source: Bosch Rexroth)

3.1.5. SafeLogic Compact (SLC)

The SafeLogic Compact (Figure 20) is a graphically programmable safety control that is certified according to IEC 61508 (SIL3), EN 62061 (SILCL3), and EN ISO 13849-1 (Cat. 4) [12]. Also modular, this system design enables optimal adaptation to a variety of different applications given the connection of desired I/O modules.

Figure 20: Example of a SafeLogic Compact (source: Bosch Rexroth)

3.1.6. IndraDrive M – HMS and HMV

The IndraDrive M is a family of modular products aimed to power and control electric motors. The HMV for instance is a power supply that can be found within the work range of 100W to 630kW [13]. Its function is to rectify three-phase AC voltage into a DC bus, which for instance can supply motor inverters IndraDrive M HMS, as shown in Figure 21. Thanks to this design, it is possible to recover energy back to the AC line or even distribute between multiple axes connected to the same DC bus.

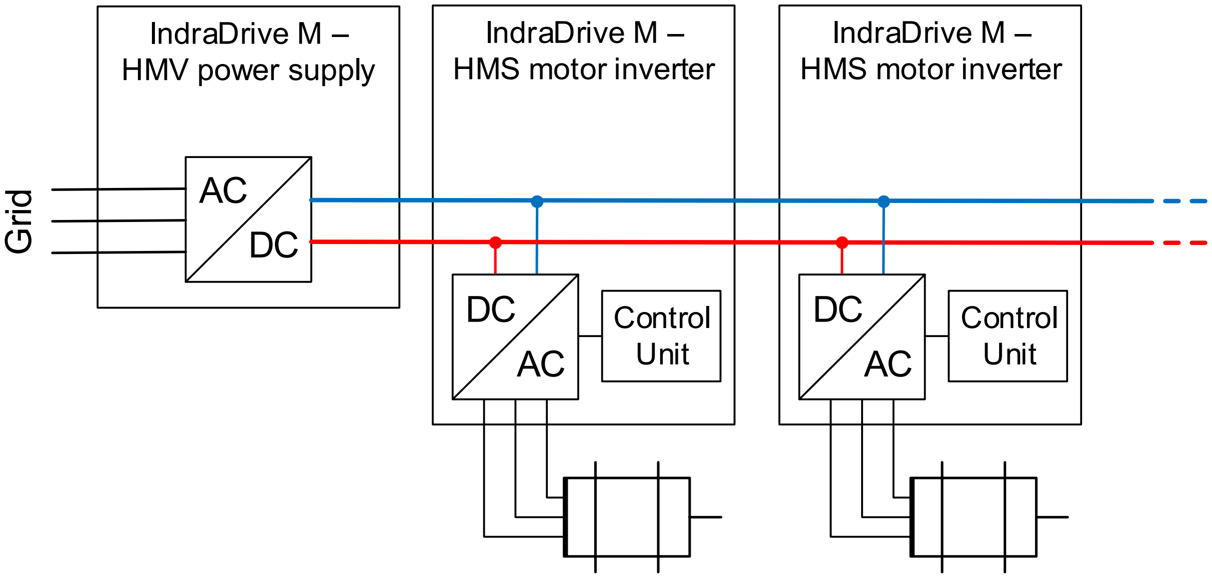
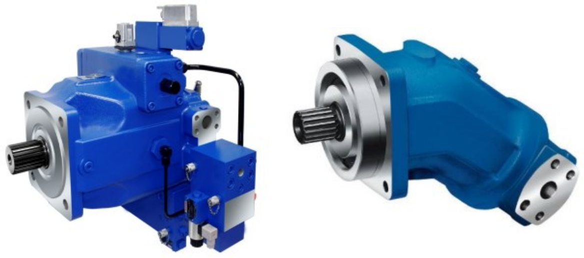


Figure 21: Products of IndraDrive M family interconnected through a DC bus

The frequency inverters hold an intelligent unit that can either control the drive itself, provided prior parameterization and programming, or receive commands from an external controller. For this purpose, it can rely on several different communication interfaces such as PROFIBUS, Sercos II and III, Multi-Ethernet, CANopen or analog voltage.

3.2. Control of the hydraulic winch

A hydraulic winch is a winch powered by a hydraulic motor, which for instance can have fixed or variable displacement (Figure 22). The hydraulic power that is supplied to the motor is usually created by pumps connected to electric motors. Depending on the application, the pumps can also have fixed or variable displacement, as posteriorly explained. Varying the combination of components and the controlled actuator, different systems can be distinguished.



A4CSG A2FM

Figure 22: A variable displacement motor with swash plate design on the left and a fixed motor with bent-axis design on the right (source: Bosch Rexroth)

The Figure 23 shows am axial piston pump with variable displacement typically used in the industry and in winch and crane systems. In such pumps, the displacement is changed by tilting the swash plate at a desired swivel angle. This shift is done by a proportional valve also installed on the pump. When the plate angle is zero, it corresponds to a null displacement, since the axial pistons do not move when rotating the axis. If the angle is maximum, the swash plate is flipped at most, creating the biggest available volumetric displacement of the pistons.

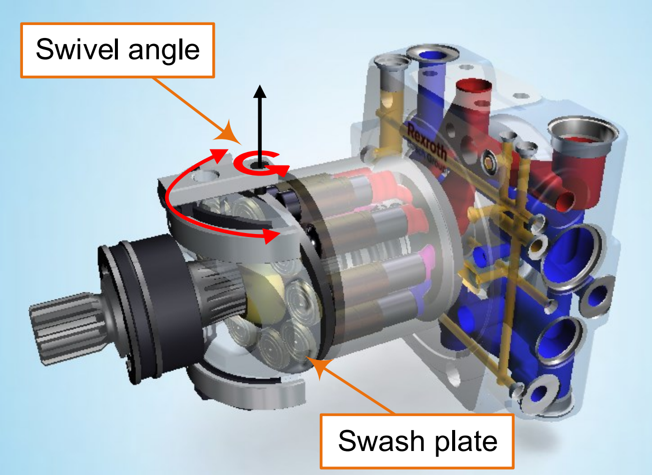


Figure 23: Transparent view of a generic variable displacement pump from Bosch Rexroth with swash plate design (source: Bosch Rexroth)

3.2.1. Open Loop

One of the most common, cheap and flexible method is called *Open Loop*. As shown in Figure 25, pumps are continuously maintaining a constant pressure line, while valves are controlling the flow to the motors. The biggest disadvantage of this system is the low efficiency, therefore making its use on winches unfeasible, since energy in a ship it usually scarce and high power systems are required to suspend loads that can vary up to 400 tons [14]. The Figure 24 express the dimension of power covered by offshore cranes.

Figure 24: Offshore crane lifting an oil platform (extracted from [3])

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[3] http://www.offshorewind.biz/2013/10/04/heavy-lift-direct-simulation-of-offshore-lifting-operations/

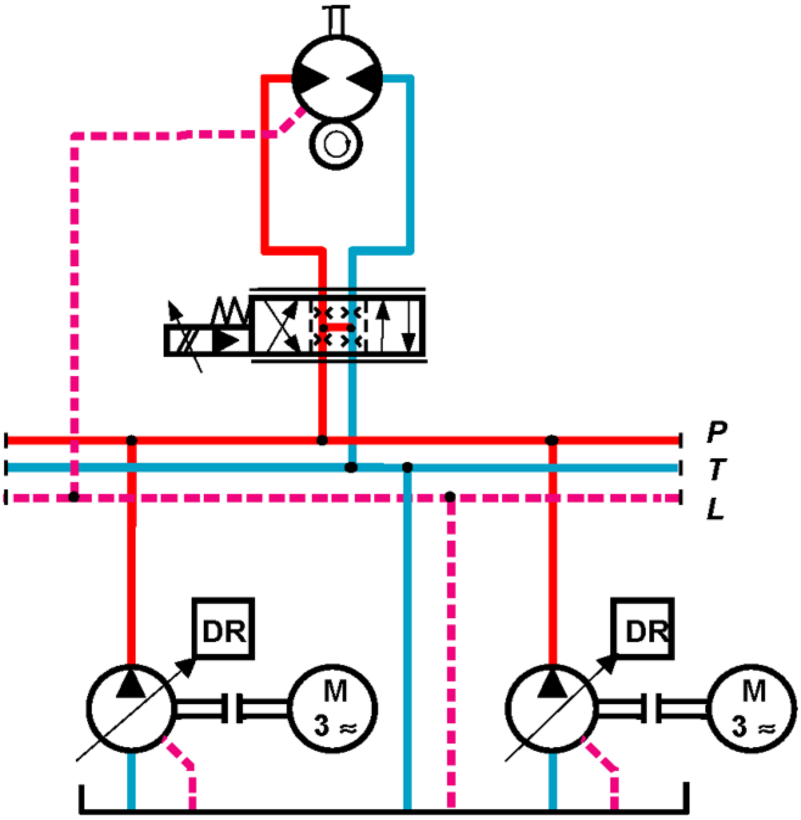

Figure 25: Hydraulic diagram of hydrostatic drives connected to a constant pressure ring (source: Bosch Rexroth)

3.2.2. Closed Loop with Primary Controlled Drive

Aiming to remove the control valves from the hydraulic circuit, the drive flow can be directly coupled to the pump, as shown in Figure 26. In this system, also called *Closed Loop*, the pump only supplies the flow required by the pump, therefore saving power when motion is not needed. The line pressure is then a result of the load on the motor shaft. Winches based on this system receive the classification PAHC.

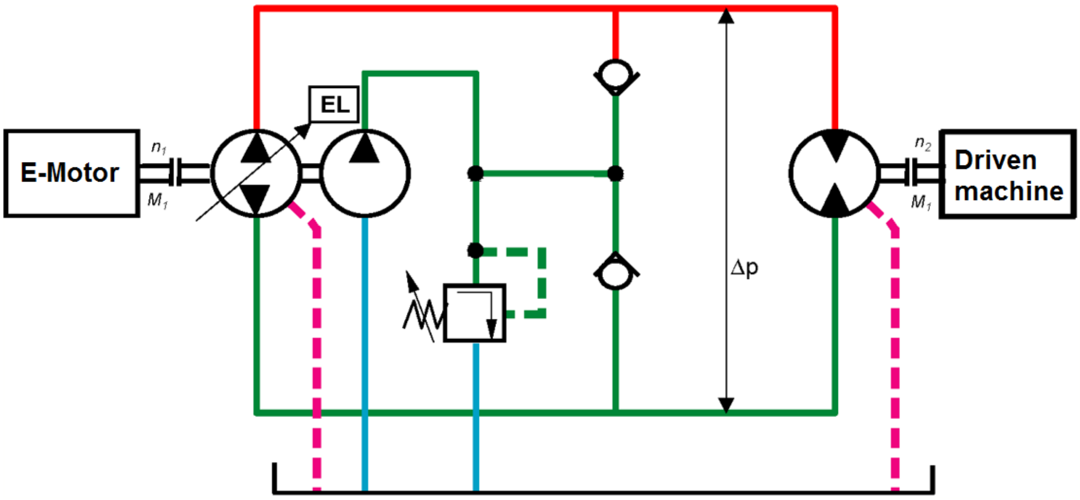

Figure 26: Hydraulic diagram of a drive with flow coupling (source: Bosch Rexroth)

Primary controlled drive systems require a variable displacement pump running with constant speed and a fixed displacement motor. In such construction, the speed of the driven machine is proportional to the loop flow, which by instance is proportionally linked to the pump swivel angle set by the controller. The Figure 27 illustrates this proportionality between the pump swivel angle and the motor speed.

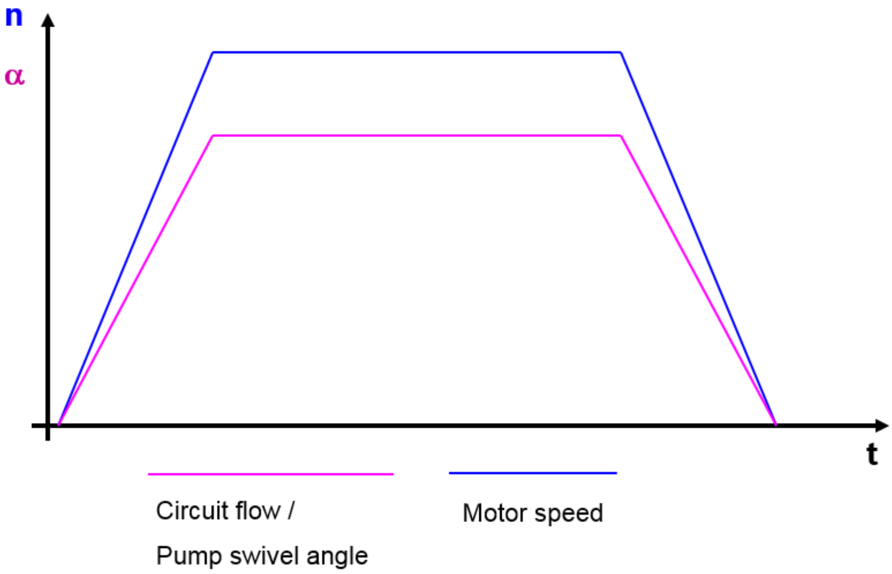

Figure 27: Relation between pump swivel angle and motor speed in primary controlled systems (adapted from Bosch Rexroth)

Although it is a cheap solution for one axis, it becomes more expensive when the system increases, as it is required one pump per motor. Another disadvantage is the low response time when increasing the length of pipes, since it suffers from the inertia and compression of the contained fluid.

3.2.3. Secondary Controlled Drive

Serving as an alternative to the previous design, secondary controlled drives are based on the swivel angle of the motor. Although the hydraulic circuit of Figure 28 may look similar to Figure 26, the purpose of the pumps, however, is only to maintain a constant pressure line, independently of the flow. Since their speed are usually constant with electric motors connected to the main grid, the pressure is maintained by varying their volumetric displacement. Afterwards, the motion controller actuates on the swivel angle of the motor in order to achieve the desired output torque and speed.

Additionally to the standard circuit, hydraulic accumulators are coupled to the pressure line. Such components can be compared to electric capacitors, as they can store energy and quickly charge and discharge. They aim not only to reduce pressure oscillations, but also to be charged when the motor is idle in order to increase available power when necessary. This design allows, for example, a crane with 720kW installed power to have 2600kW peak power (data extracted from an internal project for a knuckle boom crane). Cranes that are based on secondary controlled drives are labeled as RAHC.

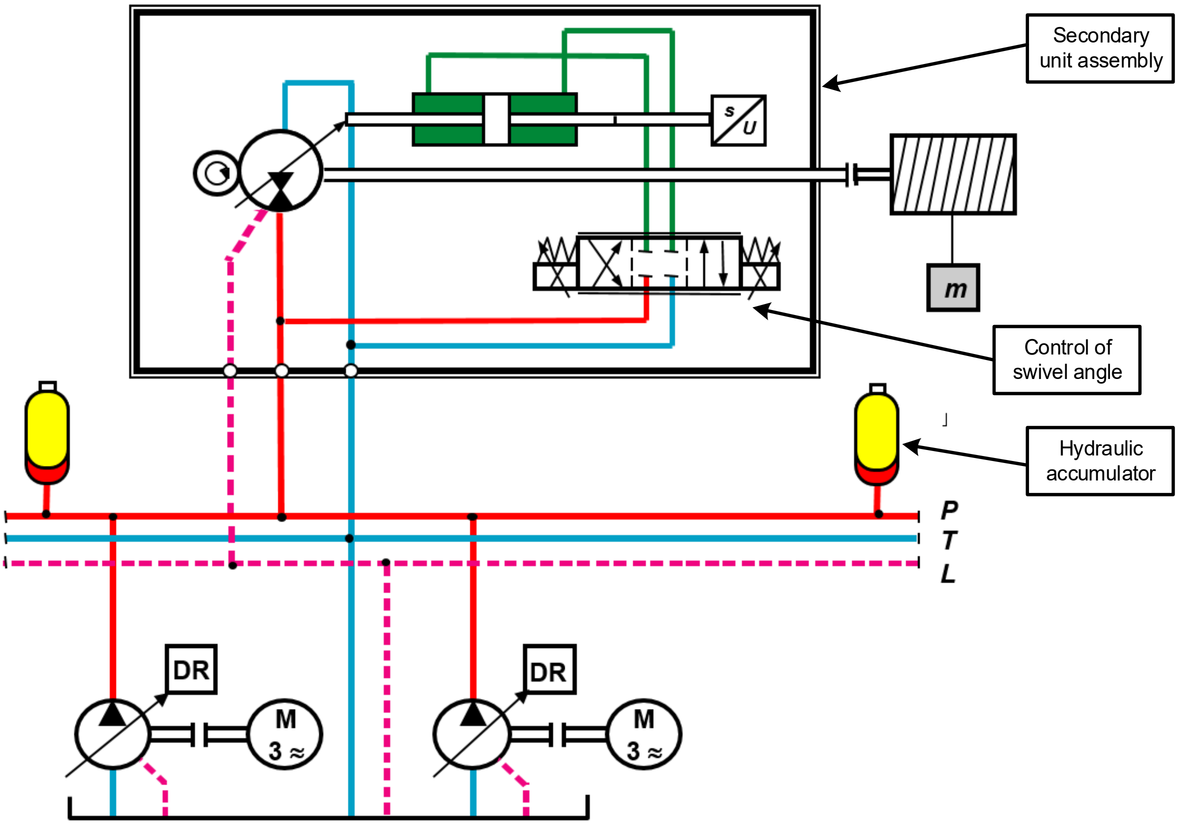

Figure 28: Hydraulic circuit of a secondary controlled drive (source: Bosch Rexroth)

In this type of control, in contrast to the primary drive, the controlled variable – the swivel angle of the motor – is proportional to the output torque, and not to the speed, as illustrated in Figure 29. This behavior impacts on a system extremely agile that can easily exceed its own limits of torque and speed, demanding a higher level of prudence in the control. This system assures the fastest response time and highest accuracy, possibility to store and recover energy in hydraulic accumulators, and ease to manage several actuators with a centralized source of power. However, since advanced control system and more accurate sensors are required, this strategy becomes more expensive than its rivals when dealing with fewer axes or simple applications.

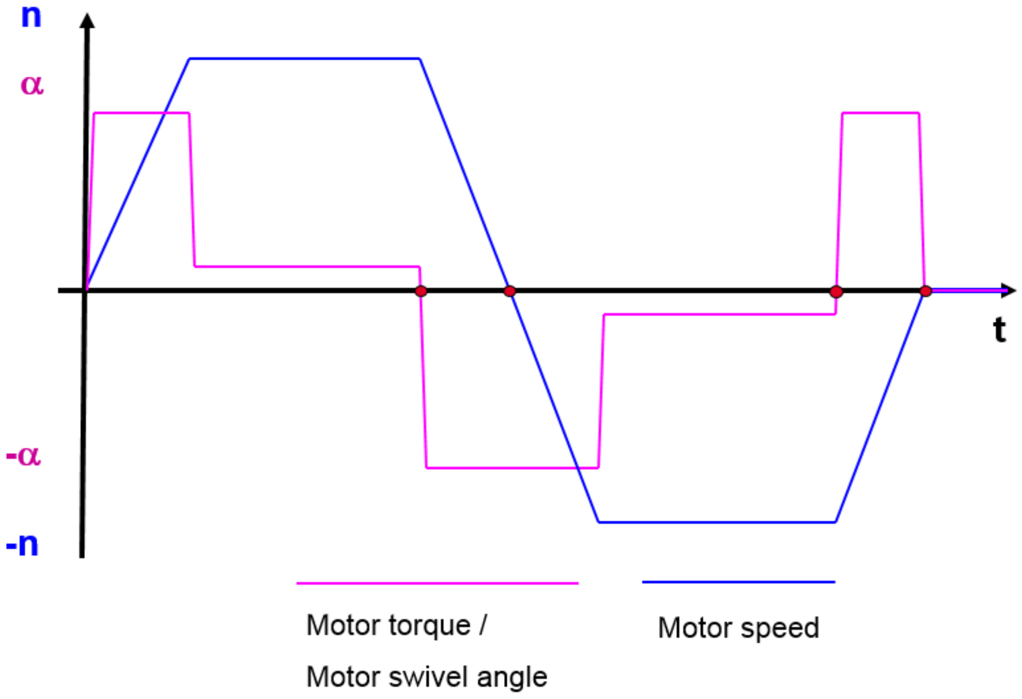

Figure 29: Relation between motor swivel angle and motor speed in secondary controlled systems (adapted from Bosch Rexroth)

4. DEVELOPMENT INPUTS

4.1. Mapping of the initial state

The process of mapping the state of the test bench can be compared to an investigation of an almost unknown system. It was firstly built by a department responsible for theater technology and lifts. Later on, another department tried to adapt it for offshore AHC purposes but the transformation has not been finished. This work started when the third involved department, “Marine & Offshore”, took over this transformation. Additionally, a fourth department with capacity in the field of secondary control has been invited to be part of the stakeholders that will use the test bench.

The first useful resource for the mapping of the initial state was the documentation created until that point. This, however, needed preparation before being used, due to the decentralization of data and lack of synchronization. Previously, digital archives were stored in several different online servers, depending on the responsible team and the country. It was then established that the information should be centralized in only one online server, without duplicates, and every team member should have access to it. In order to accomplish that, duplicates were to be filtered and classified according to the newest version.

The second pillar that supported this inspection was the hardware itself. It was especially useful due to the lack of details in the stored data. With support of a college, all cables and components of the test bench were individually verified, and from that, the respective electric plans were created. The third and last main pillar was the support of other team members, which could fulfill the remaining blind spots of this investigation.

The components of the test bench are precisely defined in later chapters. Nonetheless, a short overview sorted in three of its main aspects is presented in the next sub-chapters.

4.1.1. Structure

The installation holds two winches, one powered by an electric motor and the other by a hydraulic motor, that are together connected to a load suspended in a tower named “Lift”. The Figure 30 shows this setup on the ground floor with addition of the linear cylinder, not yet used, in the underground.

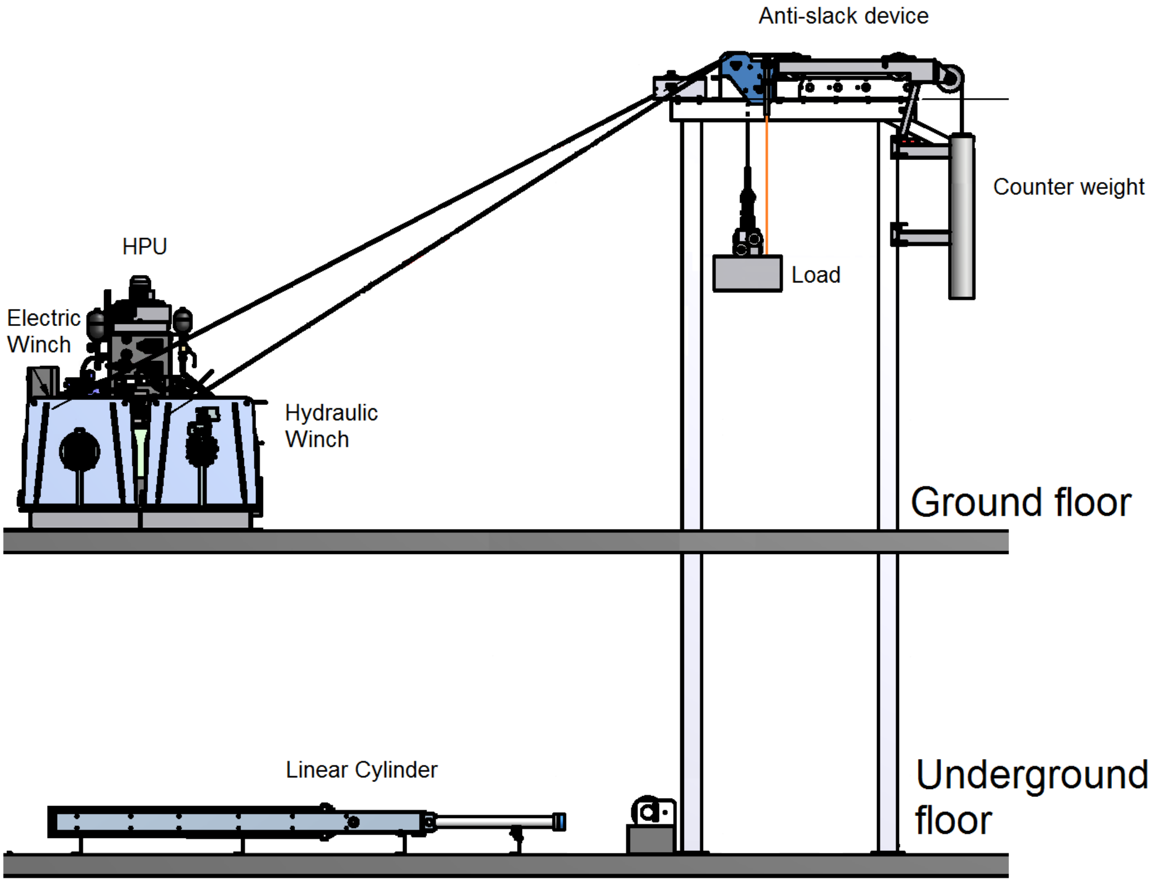

Figure 30: Drawing of the two winches connected to the lift

While the previous drawing stands for the positioning and appearance of the components, the Figure 31 presents the same setup but with a functional approach. The two winches share the same cable, which gives additional possibilities of operation. Without disconnecting anything, any winch can run alone with disregard of the other, in case the second one is stopped. However, in the scenario of heave compensation, this layout is useful for another use: With this association, one of the pair can provoke heave movements on the cable, while the other one tries to reject it and maintain the load stable. This way, the heave compensation controllers can be tested with almost any heave profile inside of the limits of the test bench.

The counter-weight's function is to keep the tension in the cable within limits. This way it avoids that the cable slacks and leaves the pulleys in case the load touches the floor.

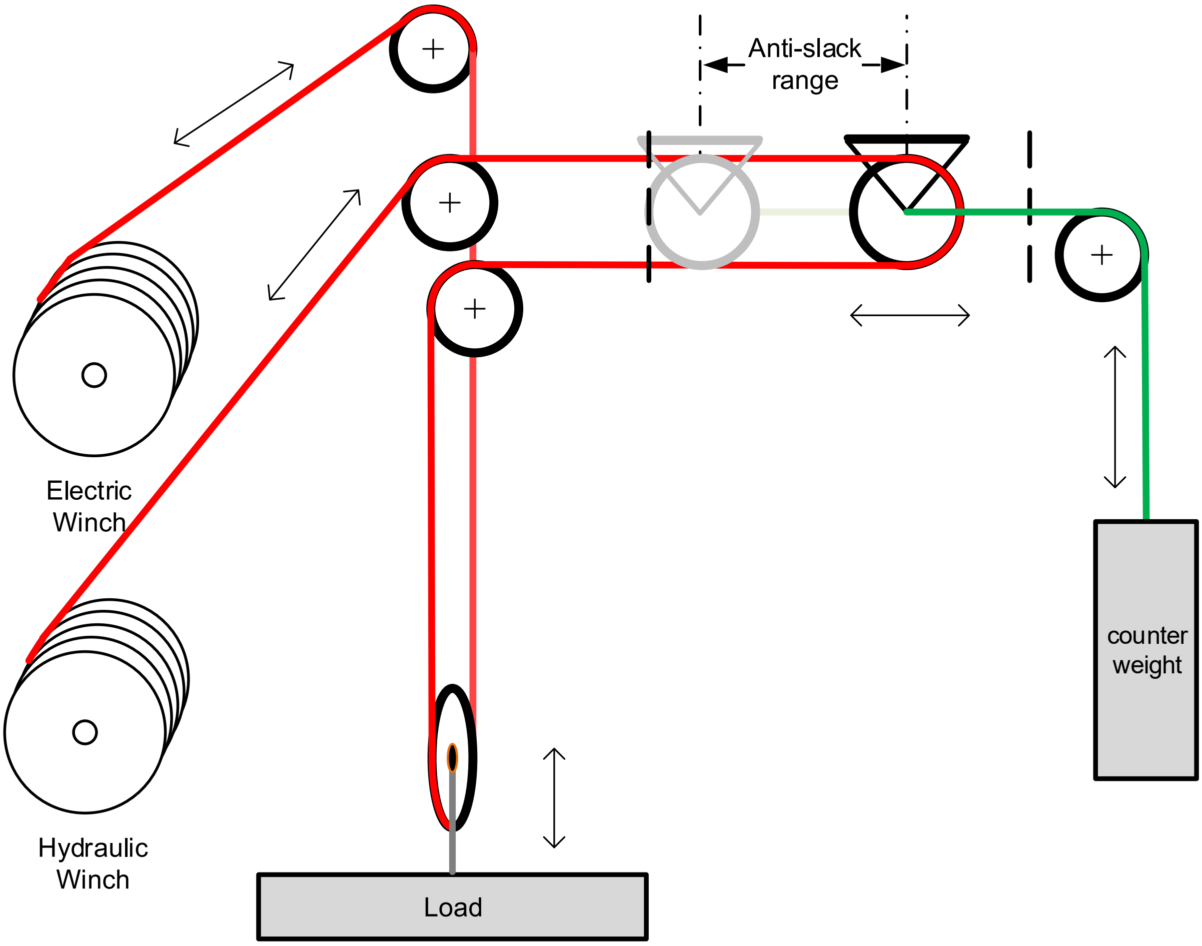

Figure 31: Functional overview of the winches and lift

4.1.2. Hydraulic aspects

In order to power the hydraulic winch, there is a hydraulic power unit (HPU) and a hydraulic accumulator available. The whole network of hydraulic connections can be only fully presented given the respective schematics and it still does not show the functionalities clearly. Instead, the Figure 32 shows a diagram containing the main functions, such as the valves connected to the main pressure pipes and the arrangement of the drives. Further components such as pilot pump, boost pump and cooling are necessary to run this system, but since they are not crucial to the understanding of the test bench, they are not included here.

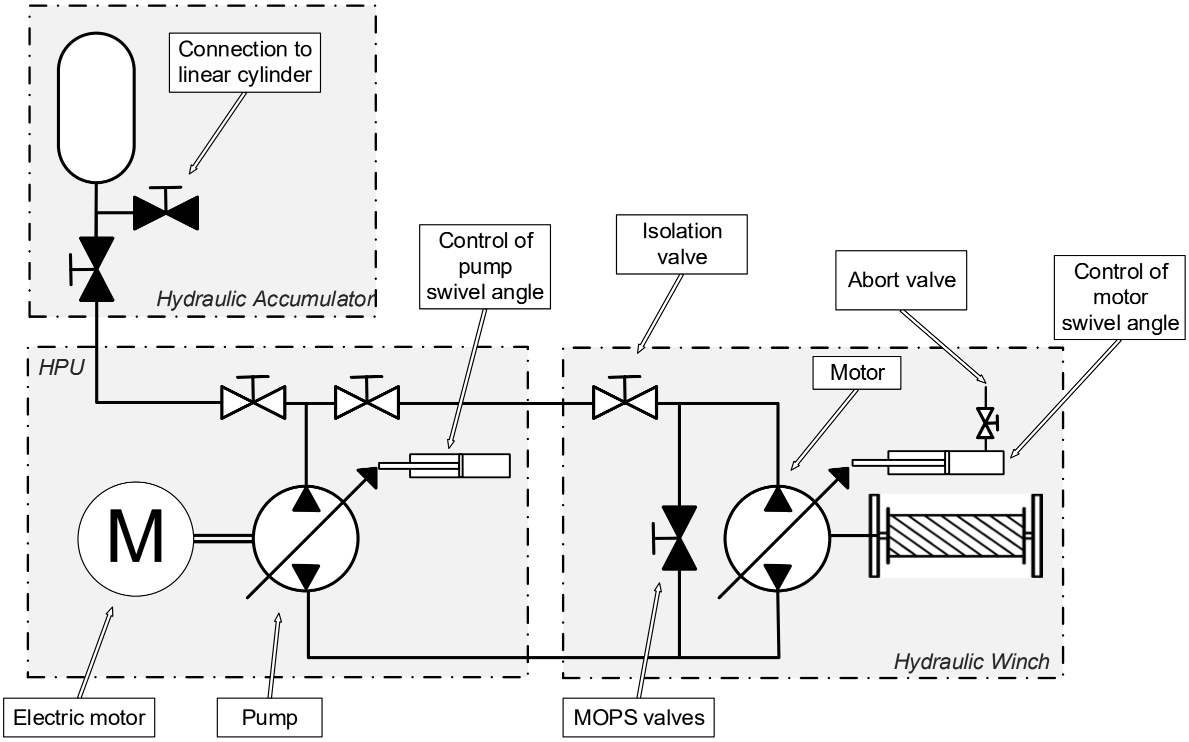

Figure 32: Simplified hydraulic circuit of the test bench

4.1.3. Electric aspects

In order to understand how the test bench can be controlled, it is necessary to know its electric interfaces. Although this has been done with the creation of the electric schematics, it is not clear enough to visualize and understand the whole system. Therefore, an overview model was desired and the Figure 33 was created. This helped bringing an initial grounding to the team members that recently joined the project. In this model, each gray box represents a physically isolated unit and their titles are cited throughout this document.

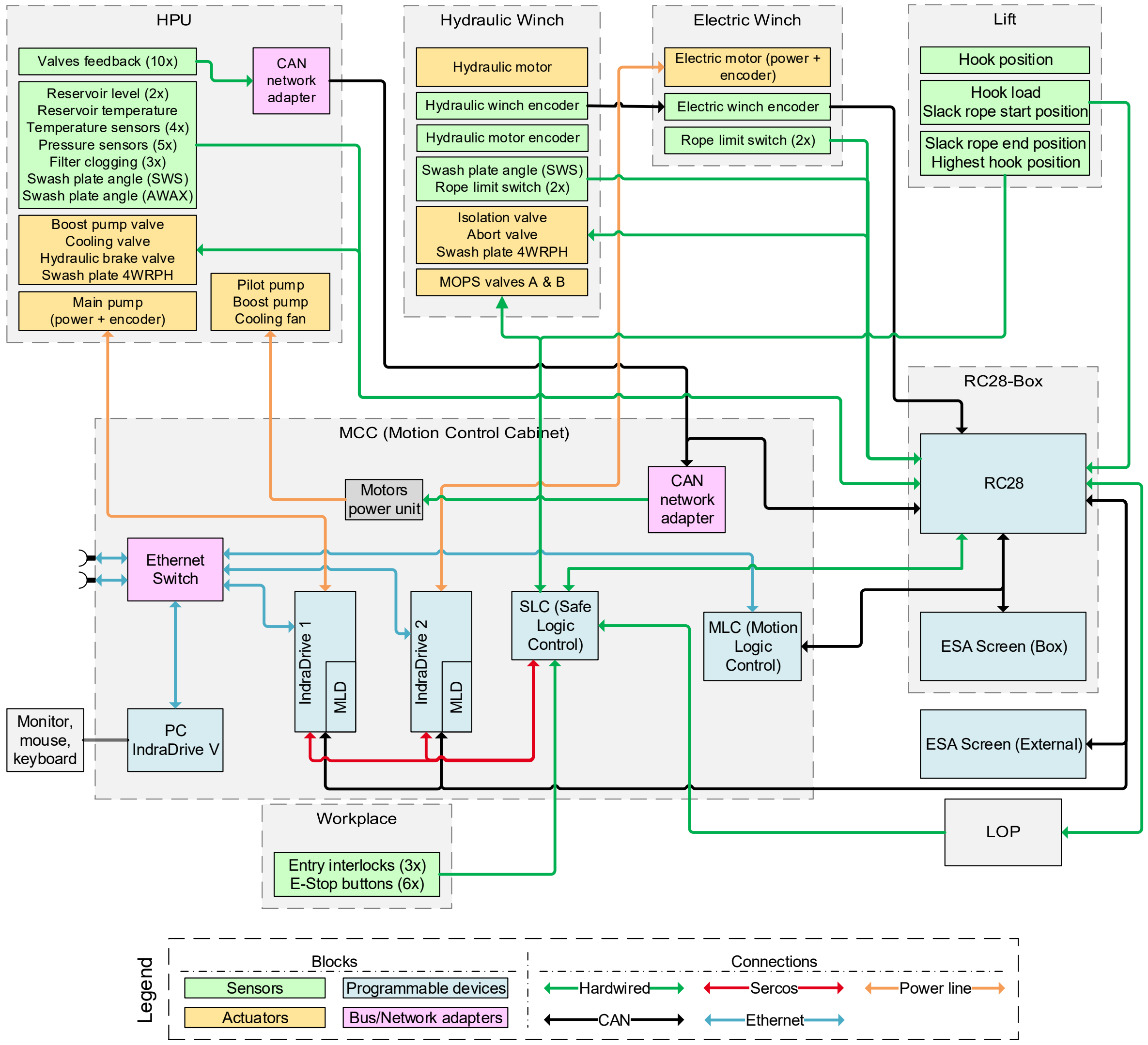

Figure 33: Electric diagram of the initial state of the test bench

4.2. Formulation of system requirements

With foundation on the analysis and presentation effectuated in Chapter 2.2, the technique of *Requirements Engineering* was applied and demonstrated in this section.

Before the highest-level requirements can be established, it is necessary to define the stakeholders of this project. In this case, instead of listing only single individuals, they were grouped by interest and working department. Their names and departments, however, are omitted from this document. Although four stakeholders are shown in Table 3, the last one, “Electric Systems”, has later become part of “Marine & Offshore” and therefore not cited in this document anymore.

Table 3: Test bench stakeholders

Stakeholder index	Stakeholder title
I	Marine & Offshore
II	Secondary Control
III	Stage Technology
IV	Electric Systems

For the understanding of the stakeholder requirements, use scenarios were adopted. They complement the description of the stakeholder’s ideas and needs, expressing them in a more user-oriented form. This can be also be seen as the description of the different operation modes, which for instance are highlighted in blue in Figure 34. Attached to them, are labels that indicate which stakeholder stands for that mode.

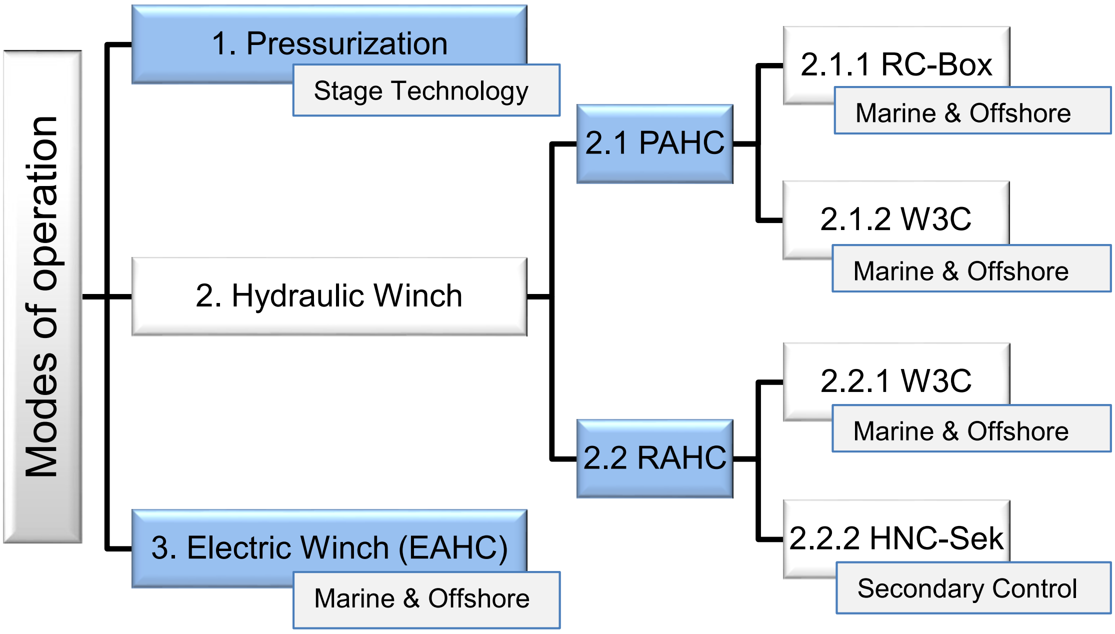

Figure 34: Modes of operation of the test bench

Each mode of operation consists of the four phases displayed in Figure 35. The first one establishes the configuration that the test bench should be set prior to initializing the controls. During the start-up, the user needs to pass through a sequence of actions in order to get the system running (operation phase). The last phase, called deactivation, defines the steps necessary to shut down the system.

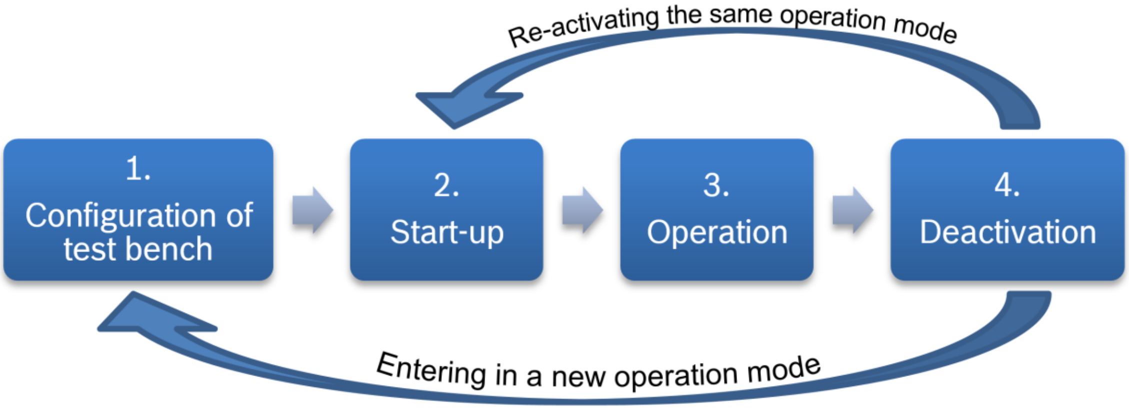

Figure 35: Lifecycle of an operation mode

The routines of two use scenarios are described in Table 4 and Table 5. They represent the control of the hydraulic winch using PAHC and the pressurization of the hydraulic accumulator for further use by the linear cylinder.

Table 4: Use scenario for the control of the hydraulic winch using PAHC

1. Configuration	☑ The load of the lift shall be connected to both winches using the appropriate cable. ☑ The hydraulic circuit of the hydraulic winch shall be connected to the HPU. ☑ The hydraulic accumulators shall be disconnected from the HPU. ☑ The RC-Box or the W3C shall be connected to the control cabinet.
2. Start-up	1. The user turns the control unit on; 2. The user sets the operation mode to “PAHC – Primary Control”; 3. The control unit turns on background functions of the HPU. 4. The control unit sets the swivel angle of the hydraulic motor at maximum value.
3. Operation	• The control unit monitors the test bench safety related functions. • The control unit monitors the status of the HPU functions. • The control unit activates the hydraulic pump at constant speed. • The test object controls the swivel angle of the pump.
4. Deactivation	1. The hydraulic winch is stopped and the brake is applied; 2. The main pump is deactivated; 3. The HPU is deactivated.

Table 5: Use scenario for the pressurization of the hydraulic accumulator

1. Configuration	☑ The load of the lift shall be connected to the linear cylinder using the appropriate cable. ☑ The hydraulic accumulators shall be connected to the HPU. ☑ The hydraulic accumulators shall be connected to the linear cylinder ☑ The hydraulic circuit of the hydraulic motor shall be disconnected from the HPU.
2. Start-up	1. The user turns the MCC on; 2. The user sets the operation mode to “Pressurization of accumulator”; 3. The user sets the desired pressure working range; 4. The control unit turns on background functions of the HPU. 5. The control unit sets the swivel angle of the hydraulic pump at maximum value.

3. Operation	• The control unit monitors the status of the HPU functions. • The control unit activates the hydraulic pump at a constant speed when the pressure in the accumulator drops below the pre-set threshold.
4. Deactivation	1. The main pump is deactivated; 2. The hydraulic accumulator releases all stored pressure; 3. The HPU is deactivated.

After the election of the stakeholders and creation of use scenarios, the requirements can begin to be engineered. This is a specification list with illustrative models that covers different levels of details, varying from stakeholder requirements to sub-system requirements. Due to the extensive amount of details, it is included later in this document in the APPENDIX A – Requirements specification. Nonetheless, in order to fully understand this work, it is recommended to read this section as well.

5. DESIGN OF SYSTEM ARCHITECTURE

Normally, the progress of the system requirements specification leads the designer until the specific lower level of technical details. However, since this project was not starting from scratch, the system design would have to take into account also the actual status of the test bench and components previously bought. This aims to prevent rework of structures that are already built and are also suitable. This chapter covers this comparison and the evaluation of a diagram containing all electric connections related to the previously defined sub-system “control unit”. The kickoff of this assignment is done by allocating the provided functionalities to the respective control hardware.

5.1. Description of functionalities

5.1.1. Motion Logic Control (MLC)

5.1.1.1. General Monitoring

Among the currently available controllers in the test bench, the IndraMotion MLC is, in terms of computing power and interface capabilities, the most powerful and versatile. Therefore, it is chosen as the central processor, which means that it would be permanently located at the test bench, responsible for monitoring all peripherals and interfacing with attachable test objects. Furthermore, the MLC shall also be apt to take over new functionalities not yet outlined.

5.1.1.2. Control of HPU background

The hydraulic power unit (HPU) can be seen as a complete and independent system with several actuators and sensors. Its principal function is to provide hydraulic power through the main pump. However, to do this, it requires the correct operation of several internal sub-systems (e.g. pilot pressure, boost pressure, appropriate oil level and temperature…). Therefore, it is established that these background operations and monitoring deserve a separated approach in comparison to the control of the main pump itself. The functionality described here covers the background devices and does not include the control of the swivel angle of the pump.

5.1.1.3. Pressurization of the hydraulic accumulator

As described in the use scenario of Table 5, the MLC is responsible for maintaining the pressure in the hydraulic accumulator inside a pre-defined range. The stored power is later used by a linear cylinder that does not belong to the scope of this project.

5.1.1.4. Control of constant pressure on the pump when in RAHC mode

When the test object desires to control the hydraulic winch based on secondary control, it does not interface directly with the hydraulic pump, but only with the swivel angle of the motor located at the winch. In order for the pump to supply the required constant pressure explained in Chapter 3.2.3, a mechanical self-controlled swivel angle valve, which works entirely based on a pre-set screw adjust, is usually adopted. Such system uses the pressure of the pump output to actuate the same cylinder that controls the swivel angle, as drawn in Figure 36.

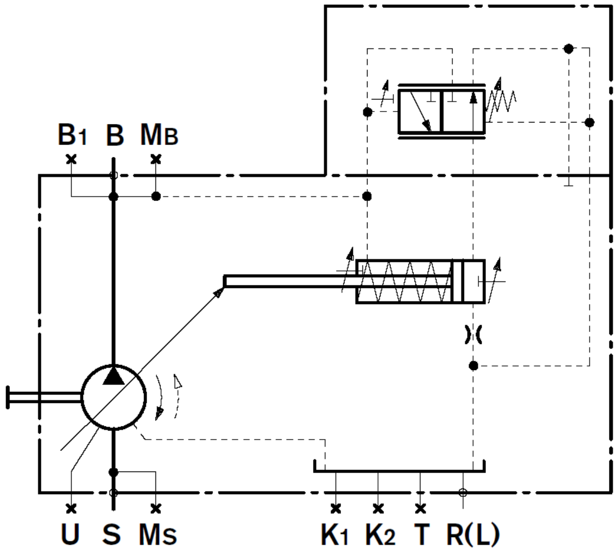

Figure 36: Hydraulic circuit of the swivel angle control embedded in the axial piston variable pump A4VSO from Bosch Rexroth (extracted from [15]*, page 13)*

However, in this test bench, the valve responsible for maneuvering the swivel angle is operated electrically and therefore an external controller is required. This is a control that is not encountered in the test objects, since it is not required in field applications. For this reason, the MLC is left in charge of accomplishing this task.

5.1.1.5. Activation of the electric winch

Although no significant thoughts were made on electric winch by the time this document was written, it is expected to be operated though the MLC and therefore the essential hardware shall be left connected.

5.1.2. SafeLogic Compact (SLC)

5.1.2.1. Secure test bench against damage and injury

The SLC is responsible for functions related to the safety of the machine, environment or surrounding people. To do so, it carries the highest priority in the control commands, being able to stop, deactivate or prevent the start of the test bench. The test bench already contains an installed SLC, which for instance is purely designed for safety functions. For convenience, it is selected to take over of the following topics:

- Protection against unauthorized entry of test area (door switches);
- Enable personnel to shut down the test bench in case of an emergency (emergency stop buttons);
- Protection of winches and lift when operating at their limits (e.g. position limits).

5.1.3. Test Objects

The test objects, as defined in the Appendix A, represent the controllers that are attached to the test bench in order to be tested. When operating the hydraulic winch in any mode, the test object shall have control over all the valves contained in the line between the pump and the motor. This includes the MOPS, isolation and enable valves (further description in Appendix A, page 88). Position sensors attached to the drum and in the lift are also required so that the controller recognizes the available room for movement. In order to give the controller the perception of applied force and torque in PAHC and RAHC modes, pressure transducers on the input and output of both pump and motor as well as the load sensor are essential.

When in PAHC mode, the test object has control over the swivel angle of the pump, while in RAHC it is over the swivel angle of the motor. Exceptionally in secondary controlled systems, the velocity of the motor axis responds extremely quickly to changes of the swivel angle. This high response speed summed up with backlash and reduction of speed in the gearbox end up turning the absolute encoder of the drum insufficient. Therefore, incremental encoders on the motor axis and on the drum axis are also required.

5.2. Definition of electric interfaces

Based on the previously described functionalities, the Table 6 is composed. It contains every component already installed in the test bench, with addition to new items further required. Its purpose is to define the dependency between the electric controllers with the sensors and actuators present in the test bench installation. The marked cells indicate that the specific controller requires access to the correlated hardware, which is either an actuator (output) or a sensor (input).

Table 6: Interface available to the electric controllers

Group	Actuator/Sensor	Name of sensor/actuator	Interface currently used	Signal type	MLC	SLC	Test object
HPU/ Tank	S	Tank level (error/warning)	Hardwired	Digital	X		
	S	Tank temperature	Hardwired	Digital	X		
HPU/ Pilot	A	Pilot pump power	-	-	X		
	S	Pilot filter pollution (error/warning)	Hardwired	Digital	X		
	S	Pilot pressure	Hardwired	Current	X		
	S	Valve X1 feedback	CAN	Digital	X		
	S	Valve Y1 feedback	CAN	Digital	X		
HPU/ Boost	S	Boost pressure	Hardwired	Current	X		
	A	Boost valve	Hardwired	Digital	X		
	A	Boost pump power	-	-	X		
HPU/ Cooler	A	Cooling valve	Hardwired	Digital	X		
	A	Cooling fan power	-	-	X		
	S	Cooling return filter pollution (error/warning)	Hardwired	Digital	X		
	S	Temperature input cooler	Hardwired	Resistance	X		
	S	Temperature output cooler	Hardwired	Resistance	X		
HPU/ Pump	A	Main pump A4 power	-	-	X		
	A	Control of swivel angle	Hardwired	PWM	X		X
	S	Pump swivel angle sensor	Hardwired	Current	X		X
	S	Pump line A temperature	Hardwired	Resistance	X		
	S	Pump line B temperature	Hardwired	Resistance	X		
	S	Pump line A pressure	Hardwired	Current	X		X
	S	Pump line B pressure	Hardwired	Current	X		X
	S	A4VG feed pressure	Hardwired	Current	X		
	S	A4VG filter pollution	Hardwired	Digital	X		
	S	Valve P (WRDU) feedback	CAN	Digital	X		
	S	Valve P1 feedback	CAN	Digital	X		

	S	Valve line B feedback	CAN	Digital	X		
	S	Valve line A feedback	CAN	Digital	X		
	S	Valve Hyd. Winch Brake feedback	CAN	Digital	X		
	S	Valve Accumulator of line A feedback	CAN	Digital	X		
	S	Valve Reverse bypass of line B feedback	CAN	Digital	X		
	S	Valve T1 feedback	CAN	Digital	X		
Hyd. Winch	A	Hydraulic Brake	Hardwired	Digital		X	X
	A	Isolation valve	Hardwired	Digital	X		X
	A	Enable swivel angle valve	Hardwired	Digital	X		X
	A	MOPS valve A	Hardwired	Digital	X		X
	A	MOPS valve B	Hardwired	Digital	X		X
	S	MOPS A feedback	Not yet connected	Digital	X		X
	S	MOPS B feedback	Not yet connected	Digital	X		X
	A	Control of swivel angle	Hardwired	PWM	X		X
	S	Motor swivel angle sensor	Hardwired	Voltage	X		X
	S	Hydraulic motor incremental encoder	Not yet connected	Incremental	X		X
	S	Hydraulic winch drum absolute encoder	CAN	Proportional	X		X
	S	Hydraulic winch drum limit switch (empty/full)	Hardwired	Digital	X		X
Elec. Winch	A	Electric motor power	-	-	X		
	S	Electric winch drum encoder	CAN	Proportional	X		
	S	Electric winch drum limit switch (empty/full)	Hardwired	Digital	X		X
Lift	S	Slack rope start position	Hardwired	Digital	X		X
	S	Slack rope end position	Hardwired	Digital		X	X
	S	Highest hook position	Hardwired	Digital		X	X
	S	Hook load	Hardwired	Current	X		X
	S	Hook position	Not yet connected	SSI	X		
Work Envir.	S	Ground floor door 1	Hardwired	Digital		X	
	S	Ground floor door 2	Hardwired	Digital		X	
	S	Basement door	Hardwired	Digital		X	
	S	E-Stop button MCC cabinet	Hardwired	Digital		X	
	S	E-Stop button Operator panel winches	Hardwired	Digital		X	
	S	E-Stop button RC28 cabinet	Hardwired	Digital		X	
	S	E-Stop button Stage Tech. Panel	Hardwired	Digital		X	
	S	E-Stop button Fence basement	Hardwired	Digital		X	
	S	E-Stop button Fence ground floor	Hardwired	Digital		X	

5.3. Design solution

Given the stakeholder inputs and the current state of the test bench, a solution was developed. Although some devices are accessed by only one controller, there are many exceptions. These cases must be analyzed in order to satisfy the requirements of all involved devices. Additionally, certain functionalities are planned to be executed by new electric controls and the rewiring must be as simple as possible. The Figure 33 is very important in this section, since it acts as a grounding to work on. The solution can be viewed as a set of focuses on different areas that are stated as the following sub-chapters.

5.3.1. Interface of HPU sensors and valves

The first big change required to the current wiring is related to the operation of the HPU. Because the previous design adopted the RC28 as the controller of the HPU, most sensors are connected to it. The newest design excludes the RC28 controller and leaves this task to the MLC. However, the amount of cables is not neglectable and this change can be facilitated by adopting a bus channel. As the feedbacks of the manual stopcock valves are already interfaced via CAN to a network adapter inside the motion control cabinet, the same channel can be used to transmit the information of other sensors. Nonetheless, not all sensors can be appropriately transmitted via CAN due to required reading speed and robustness. Examples of these exceptions are the transducers that belong to the pump control loop, that is, the pressure sensors located at the input and output of the pump, as well as the swivel angle sensor. The Table 7 rewrites the lines of the Table 6 that were modified with the inclusion of the devices to the CAN network.

Table 7: Update to interface regarding the inclusion of valves and sensors of the HPU in the CAN network

Group	Actuator/ Sensor	Name of sensor/actuator	New interface	Signal type	MLC	SLC	Test object
HPU/ Tank	S	Tank level (error/warning)	CAN	Digital	X		
	S	Tank temperature	CAN	Digital	X		
HPU/ Pilot	S	Pilot filter pollution (error/warning)	CAN	Digital	X		
	S	Pilot pressure	CAN	Proportional	X		

HPU/ Boost	S	Boost pressure	CAN	Proportional	X		
	A	Boost valve	CAN	Digital	X		
HPU/ Cooler	A	Cooling valve	CAN	Digital	X		
	S	Cooling return filter pollution (error/warning)	CAN	Digital	X		
	S	Temperature input cooler	CAN	Proportional	X		
	S	Temperature output cooler	CAN	Proportional	X		
HPU/ Pump	S	Pump line A temperature	CAN	Proportional	X		
	S	Pump line B temperature	CAN	Proportional	X		
	S	A4VG feed pressure	CAN	Proportional	X		
	S	A4VG filter pollution	CAN	Digital	X		

5.3.2. Interface of motor drives

All electric motors including the cooling fan and the pumps have their drives inside the motion control cabinet (MCC). However, they were previously controlled by the RC controller through a CAN bus as shown in Figure 37. With exception of the IndraDrives, the commands still had to be converted into digital electrical signals to interface with the motor activation modules.

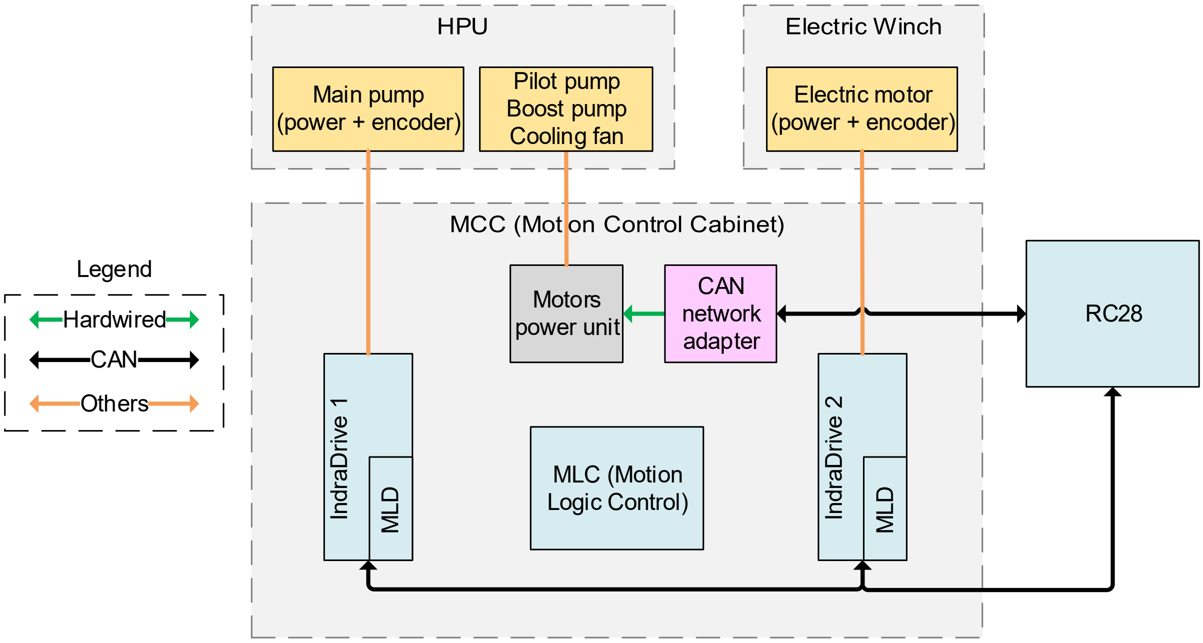

Figure 37: Previous interface to motor drives

Since the MLC that is already inside the MCC shall take over all these functions, the interface to the motor contactors is also updated to improve cleanness and simplicity. The CAN adapter interfacing the motor power unit of the pilot pump, boost pump and cooling fan becomes useless and is excluded from the new design, leaving only a direct hardwired connection in place. Since the IndraDrives offer a better support of Sercos over CAN network, this bus is adopted to interface with the MLC. This includes faster transmission and availability of more complete software libraries, reducing posterior programming work. The Figure 38 shows the updated connection of the motor drives.

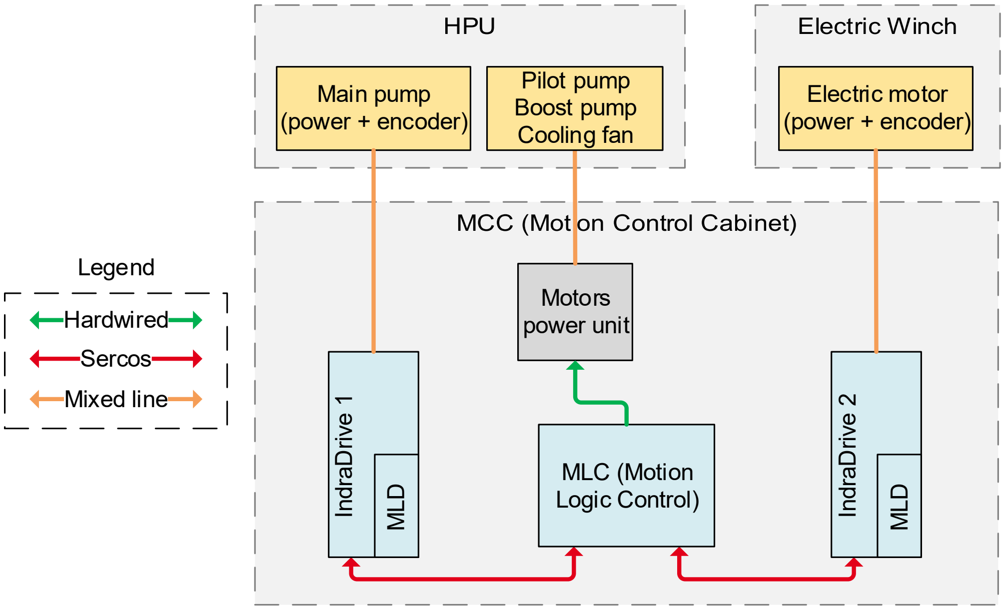

Figure 38: New interface to motor drives

5.3.3. Electric hardware on the hydraulic winch

In order to fulfill the exigencies imposed by the test objects, changes in the hydraulic winch are needed. Although its hydraulic functions are already valid, there are essential sensors missing.

5.3.3.1. Measure of motor torque

In order to run the system on secondary control mode, the algorithm executed on the connected W3C or HNC relies on the reading of the motor torque. This can be measured by a torque transducer on the motor shaft or calculated through the Equation 1, given the differential pressure between the hydraulic motor’s input and output ports. However, none of these solutions is installed yet. Due to simplicity and cost, the second alternative is more commonly used than a torque transducer. Therefore, this alternative is chosen for this test bench, after all it is meant to simulate a real work environment. It is worth to mention that the use of this formula, as well as the use of torque transducers, relies on parameters that cannot be precisely defined, such as the mechanical-hydraulic efficiency, and errors of other sensors, like the swivel angle sensor and the pressure transducers.

$$\tau = \frac{V_g(\alpha) * \Delta p}{20 * \pi * \eta_{mh}} \quad \begin{cases} \tau\ [Nm] = Torque\ on\ the\ motor\ shaft \\ V_g\ [cm^3] = Volumetric\ displacement\ per\ revolution \\ \alpha\ [rad] = Swivel\ angle \\ \Delta p\ [bar] = Pressure\ difference\ between\ motor\ input\ and\ output \\ \eta_{mh}\ [1] = Mechanical - hydraulic\ efficiency \end{cases}$$

Equation 1: Determination of motor torque given the differential pressure [15]

5.3.3.2. Control of swivel angle

The swivel angle control can be handled by two different controllers, the RC controller contained inside the W3C box and the HNC-Sek. However, they support different inputs for the position encoder. By default, the hydraulic motor contains a Hall Effect sensor with embedded hardware that converts the output to a range of 0.5 V to 4.5 V. This works the best for the RC controller, while it is not suitable for the HNC-Sek. The last requires the installation of an extra inductive (differential transformer) position transducer to record the swivel angle.

5.3.3.3. Measurement of motor speed

The motor currently installed in the hydraulic winch has its shaft in both sides. One of them is plugged into a gearbox and posteriorly to the winch, while the other side is connected to an incremental encoder. Such sensor transmits the steps progression digitally on two channel outputs (A and B) that are 90 degrees out of phase, allowing the recognition of the direction. Additionally, two other outputs contain the inverted curve, which are compared by the controller to identify errors in the signal transmission. The time-lapse diagram of these signals when in operation is displayed in Figure 39.

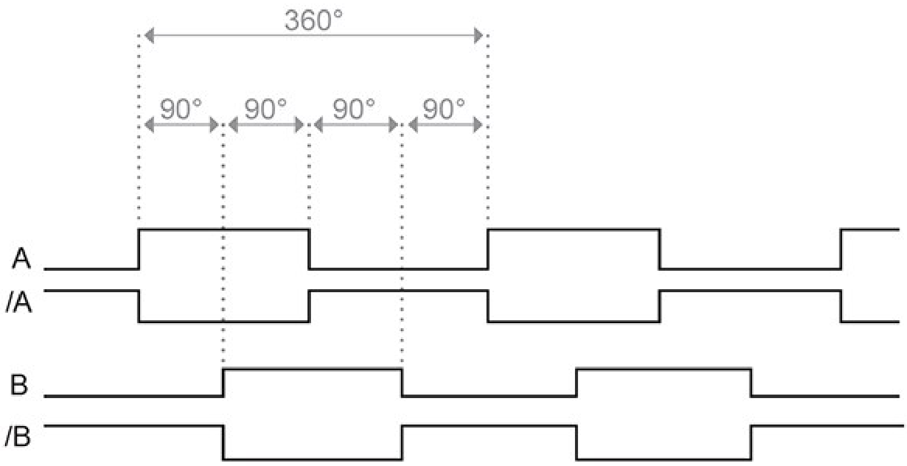

Figure 39: Time-lapse diagram of an incremental encoder that supports the signals A, /A, B and /B (adapted from [4])

The currently installed encoder generates 300 steps in one revolution, which already reaches the maximum input switching frequency rated for the RC controller. At the same time, it is seen as a weak resolution by the HNC-Sek and at least 1000 steps are necessary. Accordingly, in order to satisfy both controllers, a tandem solution provided by Lenord+Bauer was adopted and two encoders, the GEL 292 and the GEL 293, are connected in series. The mechanism that turns this possible is the pass-through hollow axis adopted by the additional encoder GEL 292, as shown in Figure 40.

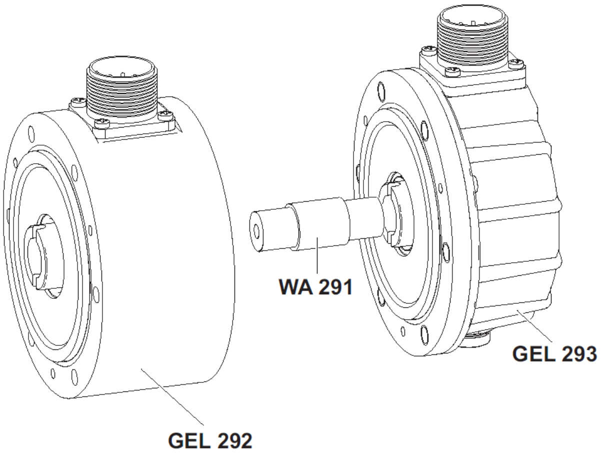

Figure 40: Tandem solution to connect two incremental encoders on one motor shaft (extracted from [5])

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[4] https://www.posital.com/en/products/communication-interface/incremental/incremental-encoders.php

[5] https://www.lenord.com/fileadmin/kundenbereich/produkte/gel290/ti290_e.pdf

5.3.3.4. Protection against overspeed

As explained in Chapter 3.2.3, secondary controlled drives demand extreme precaution over the system behavior. Due to the capability of raising quick acceleration, a faulty swivel angle control can lead the drum to rotate above its limits and provoke serious damage or injuries. In consequence, it is adequate to protect the winch against such situations. For this purpose, a safety grade incremental encoder located at the shaft of the winch's drum is used. The exact model have not been defined yet.

5.3.4. Interface between electric controls, actuators and sensors

Due to the importance of the MLC in the new design in terms of monitoring and controllability, one of the consequences in the electric design is the multiple connections that it has across innumerous devices that are also linked to the test objects. Two simple layouts can be pointed out to solve this conflict of signal sources and recipients. The first is modelled in Figure 41, where the MLC works as a processor and as an interface between the controlled hardware and the test objects. This way, just via software, the MLC is able to take over any signal, or simply link its inputs directly to the outputs and let the test object freely operate.

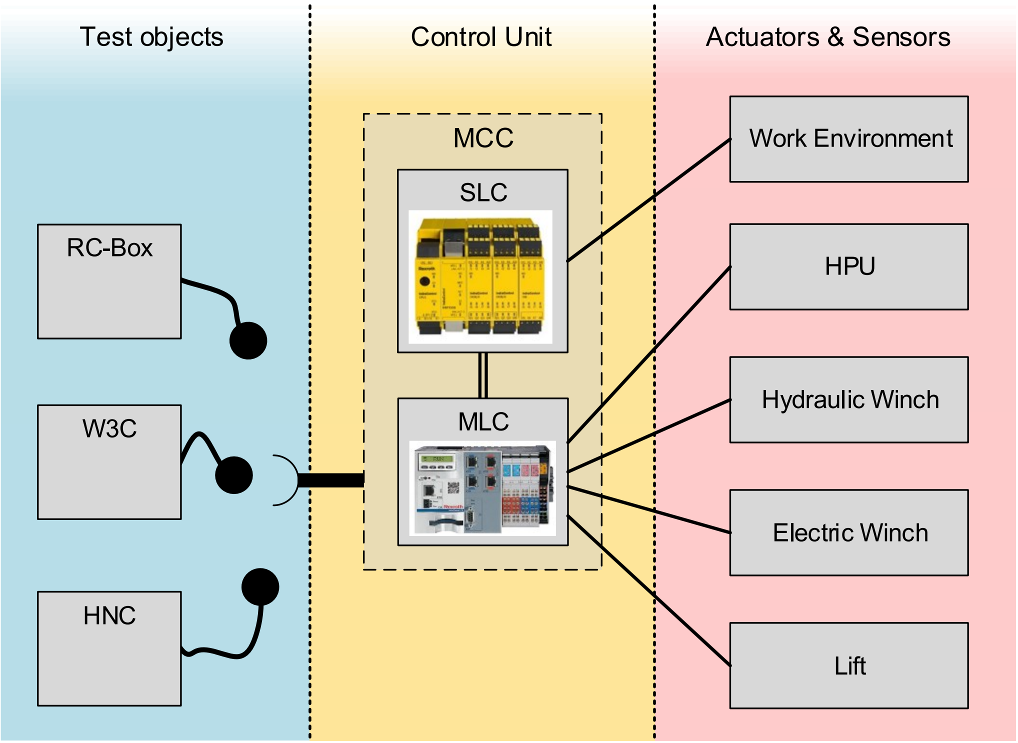

Figure 41: Model of electric devices with MCC as central bridge and core

This layout, however, has a great disadvantage regarding the delay of transmission. According to the datasheet of the available MLC device (MLC L65) [11], the minimum possible processing cycle time is one millisecond. When running the pump at maximum speed, this period of time allows it to rotate up to 19.2 degrees [15]. With addition of the communication delays, this design is considered impractical due to the lack of performance. This matter is solved by using an interconnection box that splits the signals pure electrically and without any delays, resulting in the layout of Figure 42.

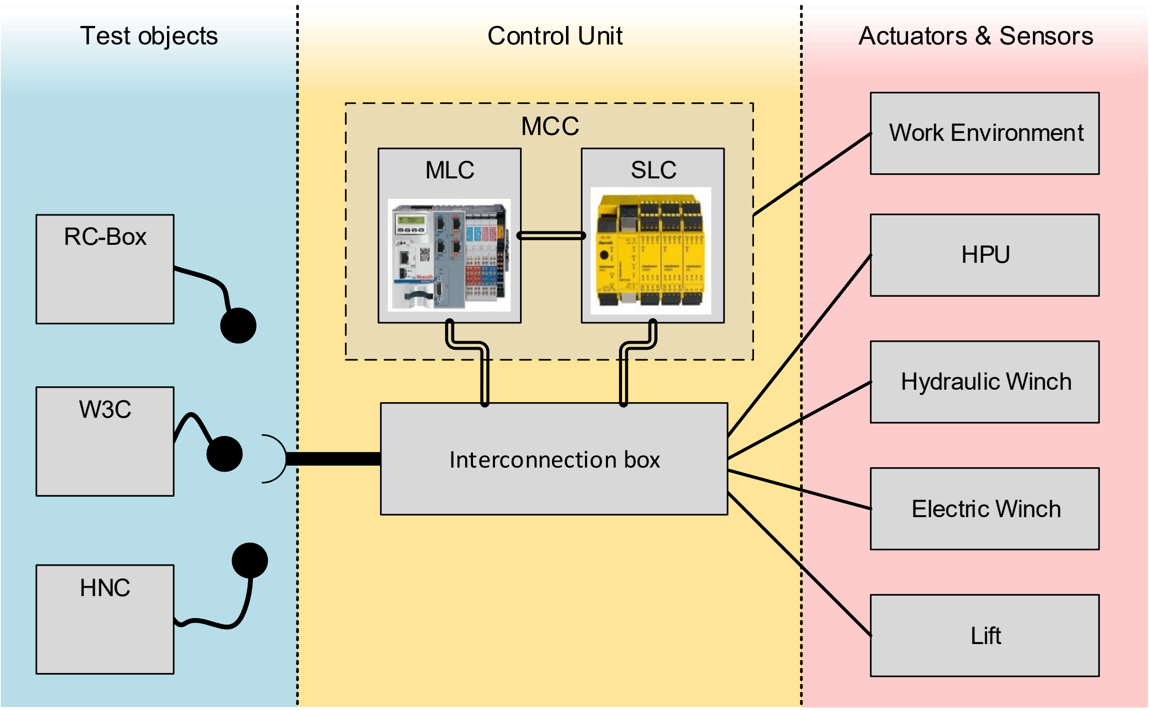

Figure 42: Model of electric devices with MCC as central core and interconnection box as central bridge

The Figure 33 shows that almost all actuators and sensors are routed to the “RC28-Box”. Since its controller is not used anymore and the box would become inoperative, it turns out to be the optimal location to place the above described interconnection box. While its interface with the actuators and sensors shall be maintained to fit each device as previously described, the connection with the MCC controls can be prepared from new to work the best.

The SafeLogic Compact controller takes over only signals that are exclusively related to the safety of the test bench. One of the reasons it was chosen for this task is due to its reliability and redundancy certifications (cited in Chapter 3.1.5). If another interfacing or converting device is introduced between the sensor and the controller, it would be necessary that it also complies with the safety standards. Hence, it is desired to connect every SLC input directly to the sensors.

The MLC, in the other hand, can take advantage of its support of Sercos communication and utilize a real-time remote I/O interface. This saves space and complexity, as dozens of signals can be fitted into only one bus between the cabinets.

It is stated by the stakeholders that only one test object shall be connected at a time, and therefore only one universal interface is determined for them. The number of connectors and pins that are necessary has not been consolidated by the time this document was written.

The following task is to solve the internal wiring of the box. Components that are free of conflict, which is, connected to only one controller, are ignored in this section. It is possible to group the remaining signals in the following categories:

5.3.4.1. Detection switches

These are represented by the limit switches of the winches' drums, which indicate if they are full or empty, and by the position switches located at the lift. These are placed in the beginning and in the end of the anti-slack mechanism (refer to Figure 56) and in the highest position allowed to the load. All switches operate with digital 24V outputs which shall be read in both MLC and test object. Due to the high impedance of the controllers' inputs, this property can be disregarded and the cables can be split into two.

5.3.4.2. Powering of valves

The pump's swivel angle proportional valve as well as the remaining switch valves shall be able to be controlled by either the MLC or the test object. The requirement imposed for this engagement is that the MLC decides whenever the test object can take over the command and what should be the output in the other case. Moreover, when the test object is in command, the MLC shall be able to read its outputs by means of monitoring. This is done similarly as in the last sub-chapter, splitting the cables into two duplicates.

The solution found for this issue is shown in Figure 43, where the switch and the Boolean "&" ("AND") functions are built from relays. Accordingly, the MLC controls the switch element depending if the test object is connected to the test bench or not. Additionally, a logic "AND" block is inserted before the valve. In consequence of this interlocking system, the test object can only activate the valve in case the MLC also allows it. This is especially important for these commands, since the powering of one MOPS valve can already hydraulically disconnect the motor from pump and drop the load freely.

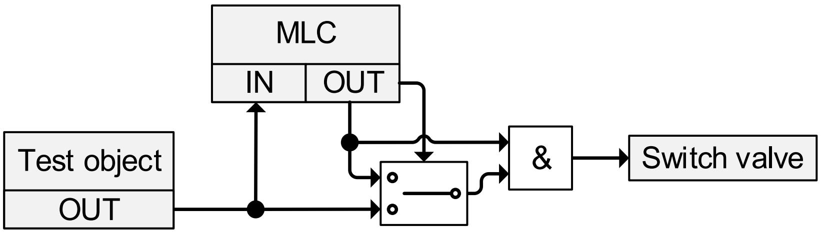

Figure 43: Diagram of valve switching with logic interlock

The static brake responsible for holding the position of the hydraulic winch is activated by a switch valve in the HPU. When unpowered, it returns to a safe state, which means that the brake requires power in order not to brake. This happens because it requires hydraulic power provided by the valve to push back the spring that brakes the winch. Since it represents a safety feature that is necessary during, for example, emergency situations, it receives a special approach in this design. Instead of the MLC, it is commanded by the SLC together with the test object. Since a command from any controller should independently be able to stop the winch, a logic "AND" is implemented.

The previous design decisions lead to the design of Figure 44.

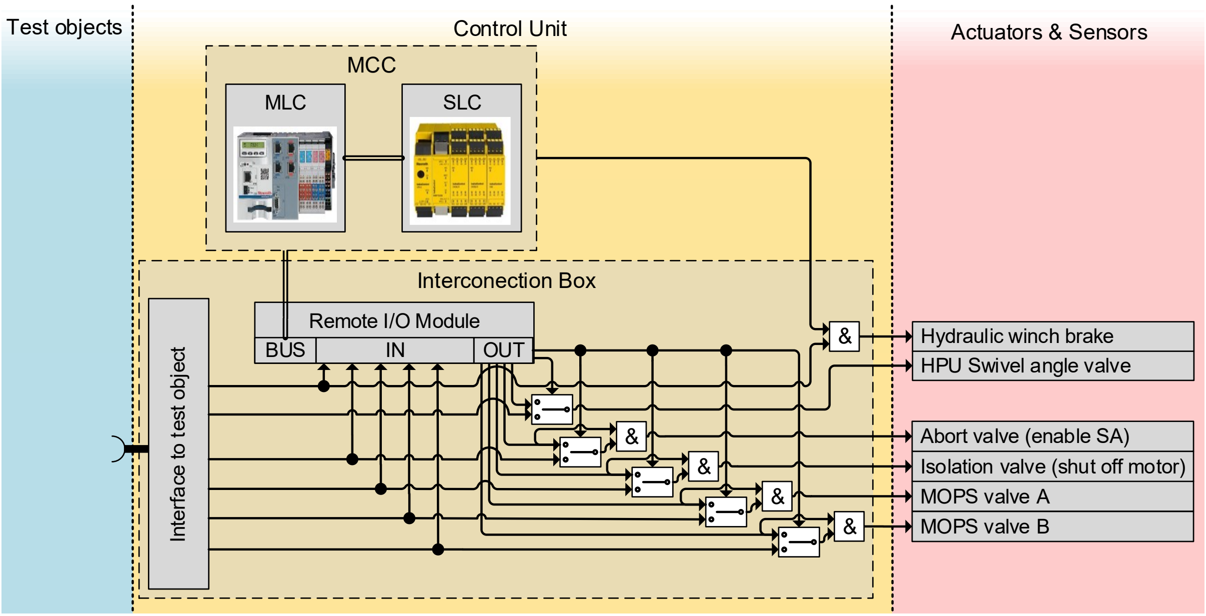

Figure 44: Complete diagram of activation of valves

5.3.4.3. Analog current and voltage signals

The employed pressure sensors, swivel angle encoders and load force sensor make use of analog current and voltage signals. Such inputs are crucial for the control of the crane and therefore transmission delays are not accepted. The solution found to duplicate these signals relies on the real-time analog signal splitter VariTrans A 20300, from Knick[6].

5.3.4.4. Absolute encoders with CAN interface

The electric and the hydraulic winches make use of absolute encoders with CAN interface to measure the angular position of the drum. In order to connect the two sensors and the two controllers (MLC and test object), the network shown in Figure 45 is created.

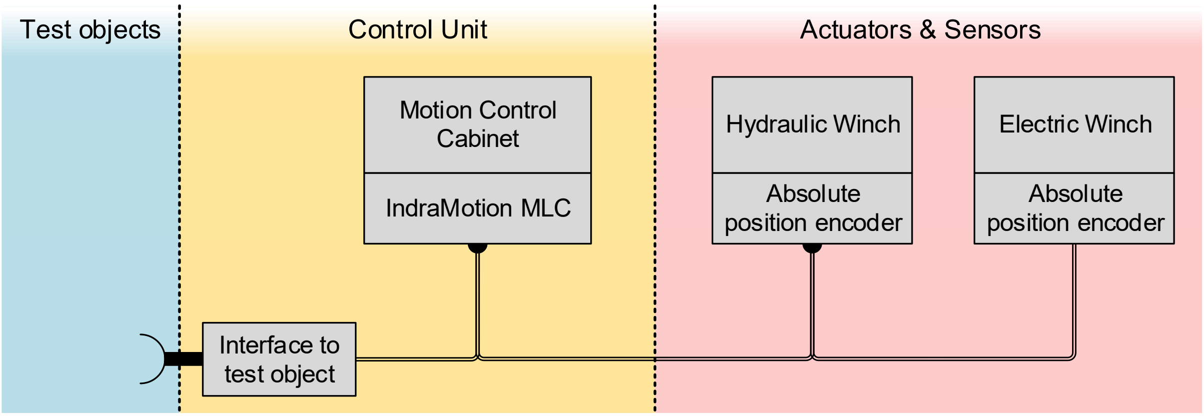

Figure 45: Arrangement of elements in the CAN network

5.3.4.5. Composition of the resulting architecture diagram

The previous individual solutions led to the formation of the broad diagram of Figure 46. It embraces both the wiring inside interconnection box and the view of the box as a whole in the test bench. Although it does not have the format of an electric circuit yet, this style of drawing was found to be more understandable and flexible during the process of converging to the optimal system solution.

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[6] https://www.knick-international.com/en/products/proline/isolated-standard-signal-conditioners/varitrans-a-20300/

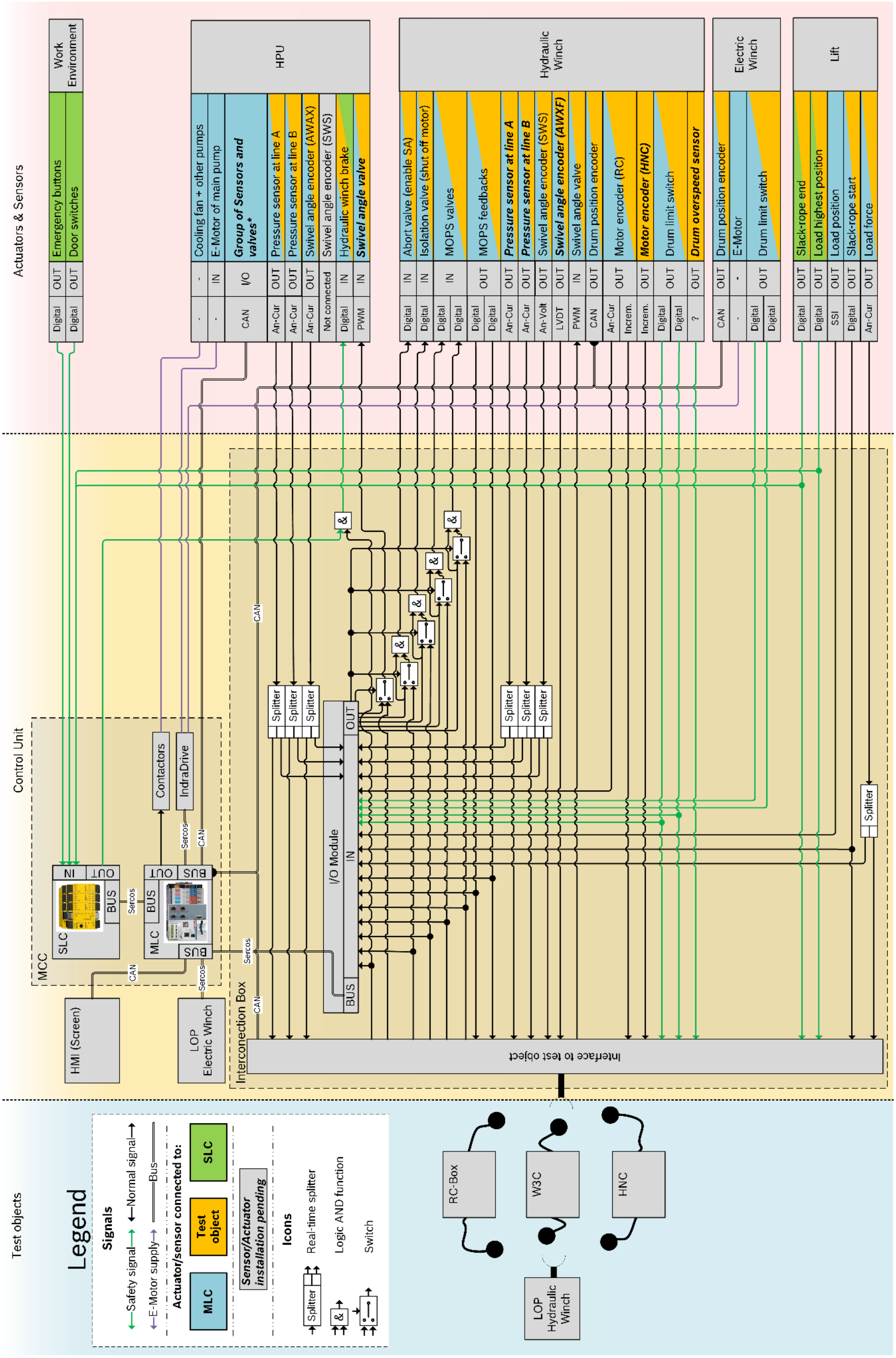


Figure 46: Diagram of electrical connections in the test bench

6. IMPLEMENTATION

6.1. Drawing and installation of the new electric circuits

Regular reviews and discussions with the stakeholders permitted the correct evolution from the stated requirements through the definition of components. At this moment, considering the solid system specification owned by the project, it can advance to the next development stage. In order to freeze the design and prepare for ordering new components, the diagrams and other reports are currently converted into electric schematics by the engineering team.

While the diagrams represent the ideas and wishes for the electric circuits, the schematics translate them to *state of the art* of the implementation. To demonstrate this, the conversion of the switching of the abort and isolation valves contained in the Figure 44 is chosen. The outcome is shown in Figure 47. The five vertical wires link the test object to the valves, while the commands 305K2 and 305K3 come from the MLC in order to operate the switches.

The first detail present in the schematic that was not foreseen is that both valves' wires are placed in the same connector C1, therefore sharing the same electric ground. The switching is then realized in the common ground and in the first and fourth connector's pins. Although the MLC can set any output (on or off) using the layout of Figure 47, differently from the initial diagram, it does not power the valves. This is because the inputs of the switches (operated by the MLC) are connected to the ground and to the 24V bus, and not to the MLC's output ports.

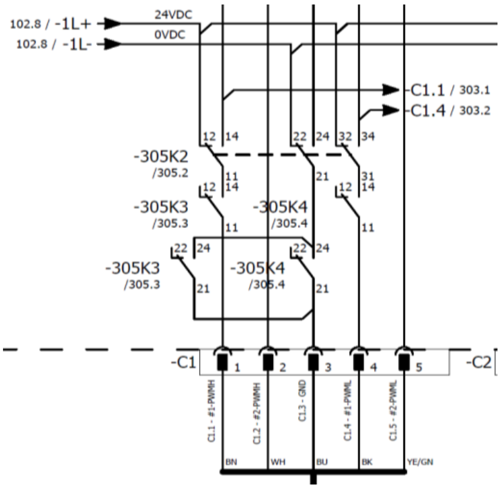


Figure 47: Snapshot extracted from the electric schematic regarding the switching of the abort and isolation valves in the interconnection box

Since the schematic drawings and following ordering of components are not under the scope of this project, further details are omitted.

6.2. Software development

After the structure and purposes of the electric controls and devices were defined, the software development finally takes place. The controllers that will accommodate lines of code are listed as follows:

- SafeLogic Compact: The SLC installed in the MCC already had working software prior to the beginning of this work. However, due to wiring changes, it needs to be updated.
- Motion Logic Control: Previously non-functional, the MLC acts as the processing core in the new test bench architecture.
- IndraDrives: Due to the change of interface, updates to the parameterization are required.

The controller addressed in this work is the IndraMotion MLC. The programming is done through the Bosch Rexroth's software IndraWorks Engineering [16], which supports all PLC programming languages listed in IEC 61131-3 [17] or direct parameterization of motion drives.

Since the HPU is the enabler of both the hydraulic winch and the linear actuator (by pressurizing the accumulator), its control is selected as the first software priority. The Appendix A and the rendered operation state machine of Figure 48 are used as groundings for this development. The overview of the expected features are described in Chapter 5.1: Description of functionalities.

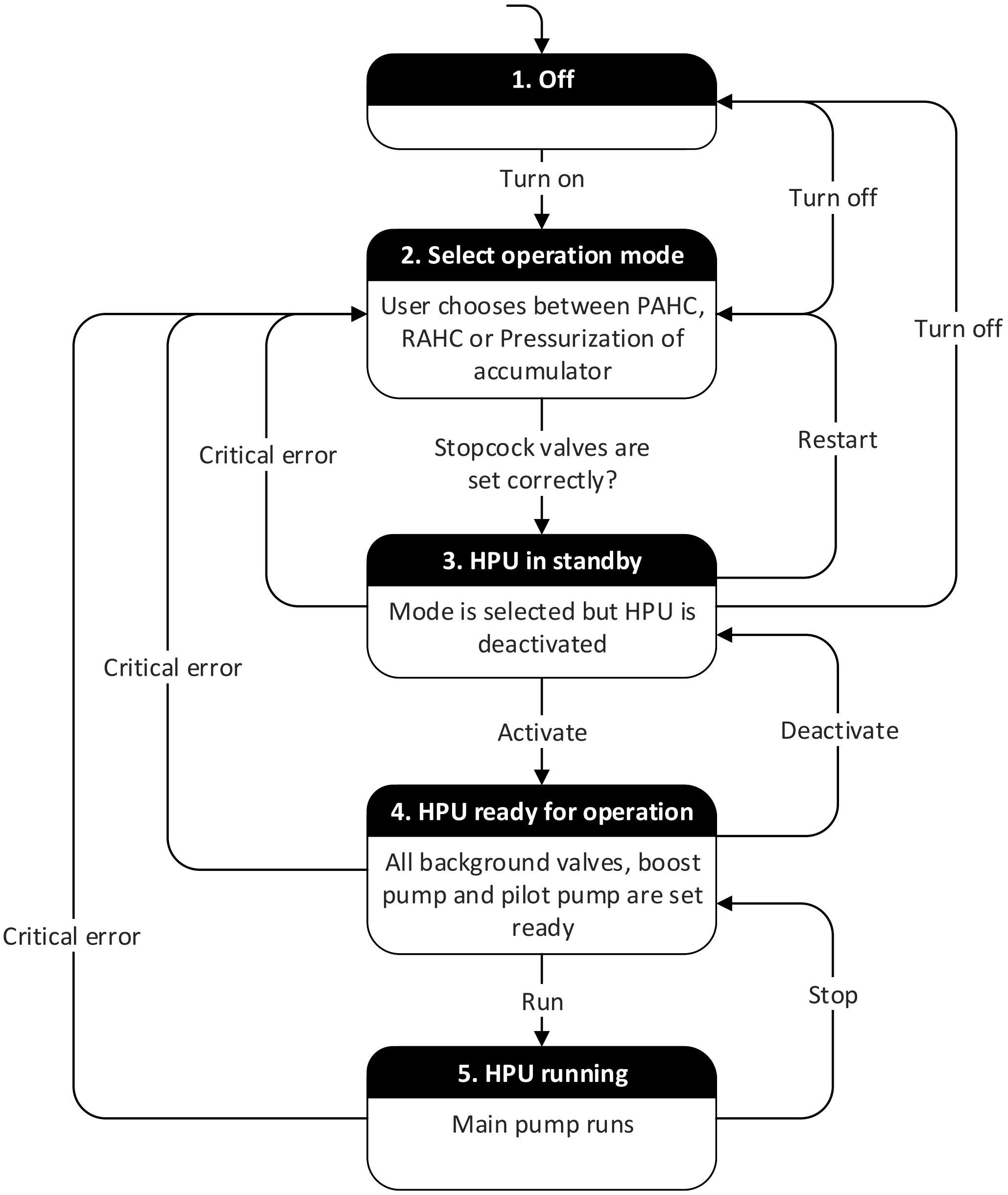
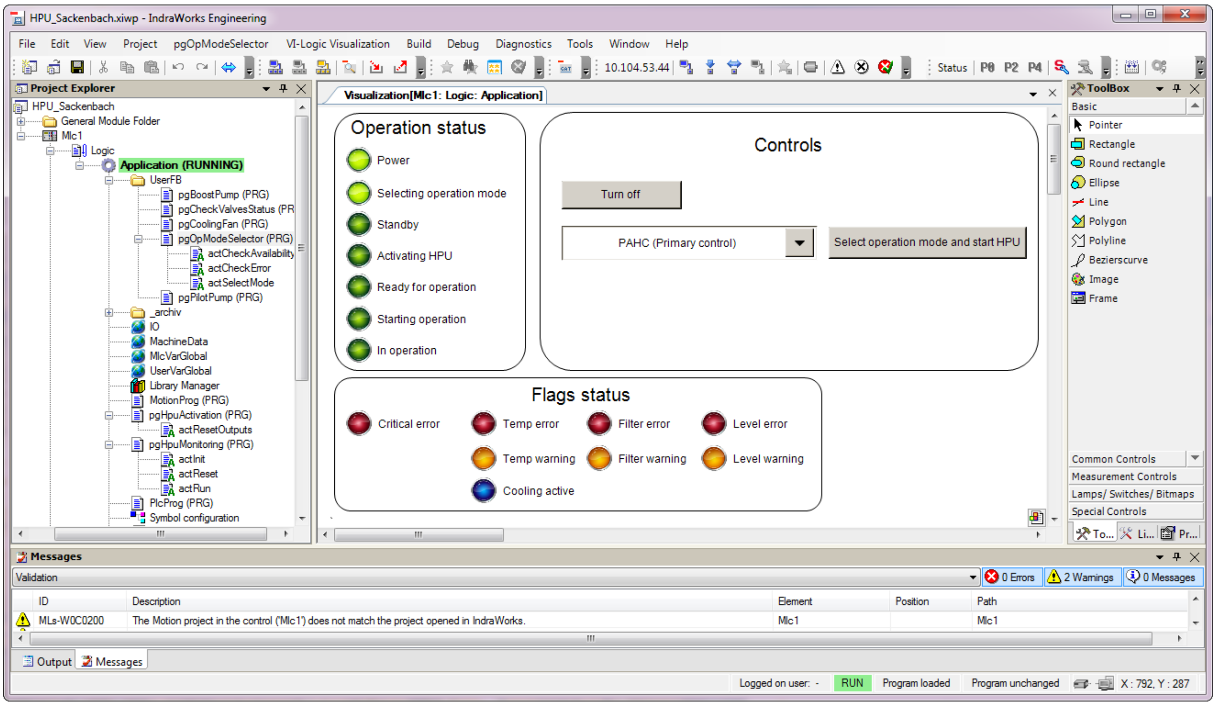


Figure 48: State machine of the HPU control operation

When installed in the test bench, the MLC is expected to interface with the operator through buttons and a screen. In order to create an environment as close as possible to the real application, a virtual graphical user interface is also designed, aiming the support of the same features. It is contained inside of the IndraWorks environment, as shown in Figure 49.



ID	Description	Element	Position	Path
MLs-W0C0200	The Motion project in the control ('Mlc1') does not match the project opened in IndraWorks.	Mlc1		Mlc1

Figure 49: Graphical user interface for the operation of the HPU

Due to the short period of time left for the development of the software, only the activation of the HPU could be approached and the fifth state of the state machine of Figure 48 was put aside. This ensures that no errors are present and all background actuators are correctly running according to each mode of operation. This startup procedure is mandatory prior to the activation of the main pump.

Since this development took place simultaneously as the new electric components and services were being ordered, it could not be tested in the test bench itself. Instead, the same MLC L65 was brought to the development office and its I/O were emulated in a virtual environment with visual interface. The Figure 50 shows this area inside the development environment. Here, every input and output is linked to buttons and indicators, therefore fully open to simulate any situation. This was then used to test the software modules prior to the evaluation in the test bench.

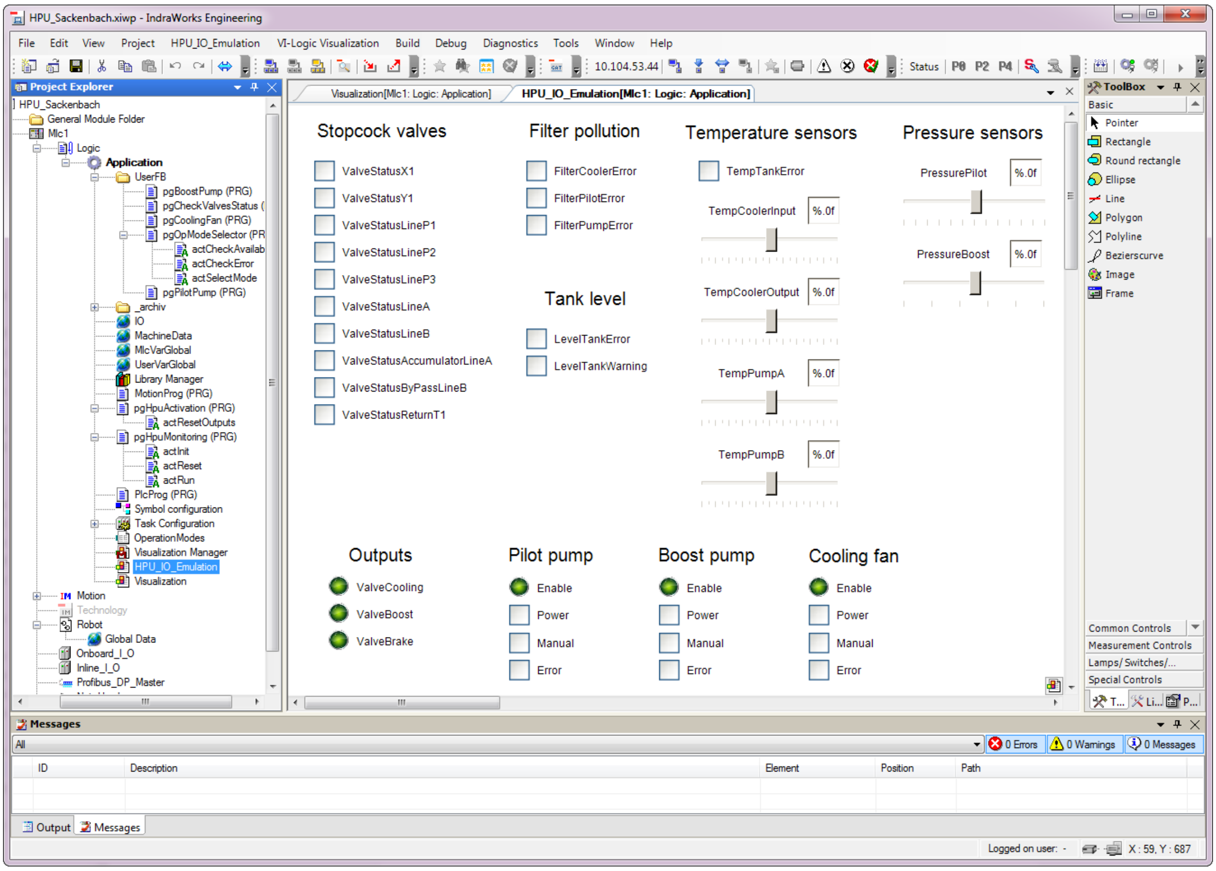


Figure 50: Visual interface of emulated inputs and outputs

7. RESULTS AND FINAL CONSIDERATIONS

This work has taken over the test bench for offshore winches and cranes, which was previously stalled, pointed the adequate development direction, and moved towards its finalization. Even though the outcome of this work did not reach the last step, the results were valuable for supporting its accomplishment. In the end, the team became satisfied with the achieved progress, which indicated the successful project approach.

The state that the test bench was initially conceived was a result of work of two independent departments that do not participate in the development anymore. Later, at the start of this work, a third branch called “Marine & Offshore”, with members in Germany and Holland, took over the development. Following this, it included as stakeholders the two initial teams and another additional group aimed on secondary controls. Hence, this work had to deal with team in four different departments, two countries and two languages. That said, this biggest challenge in this work was not technical, but social, and only such experience can teach these skills.

The performed tasks were located in management and development fields, and both required research and learning in order to properly advance. Although most of the work was focused in finding electric and software solutions, the systems were mainly hydraulic based. Therefore, good comprehension of all areas become required.

The last chapter contains the latest performed development phase, which was the implementation of the previously designed system architecture. Notwithstanding, it has not been completed yet. Together with the electric plans that are currently being created, part lists with all components necessary for the new constructions are being involved. These documents will then be used to order all hardware as well as services for their installation. In the beginning of this work, the mechanical and hydraulic slices of the test bench were already close to be done. The electric, in the other hand, evolved from a distant unworkable hardware to the purchase orders of the new system, which this time is in accordance with all stakeholders.

Due to insufficient time, the programming of only one device could take place during the progress of this work. The SafeLogic’s software still have pending changes and the IndraDrives require new parameterization in order to work with the latest communication protocol. The features so far implemented in the MLC target the activation of the HPU, which sets it ready to run the pump in the desired operation mode. To verify such features, however, it is firstly necessary to have all the electric changes implemented in the test bench installation.

It is important to mention that only the stakeholder needs with the highest priorities were primarily taken. In consequence, only little attention was given regarding the electric winch, which remains still open for future outlining.

The successor of the implementation is its testing and validation, the last step towards the creation of a test bench for verification of electric controls for offshore winches and cranes. According to the adopted development technique, this phase ensures that the implemented features respond and satisfy the requirements previously molded.

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[17] IEC 61131-3. **Programmable controllers – Part 3: Programming languages.** February 2013.

APPENDIX A – REQUIREMENTS SPECIFICATION

The requirements can be written in numerous ways according to what the designer is looking for, or to the level of description that it belongs. In this document, they will be displayed in a textual form and divided by different levels. The attributes that are present in every single statement is the requirement identifier and its name. These are unique and cannot be duplicated. The requirement's name shall contain a compact, direct and unambiguous sentence that summarizes the requirement. The first three characters of the identifier indicates the level of requirements that it belongs to, as explained in Table 8. Right after that, as illustrated in Figure 51, three digits form an identifier number. The first digit of this number stands for the corresponding sub-system, as specified in Table 9. The last two digits are a counter that starts in 01 and increases after every new entry.

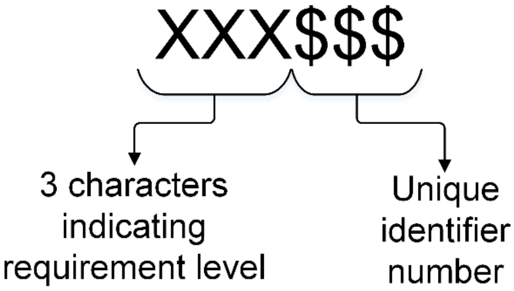

Figure 51: Classification of requirements identifiers

Table 8: Explanation of identifier characters

Identifier Characters	Corresponding Requirement Level
SHR	Stakeholder requirement
SYR	System requirement
SSR	Sub-system requirement
CPR	Component requirement

Table 9: Explanation of identifier number

Identifier Number	Corresponding Sub-System
1$$	Control Unit
2$$	Hydraulic Power Unit (HPU)
3$$	Accumulator Unit
4$$	Hydraulic Winch

5$$	Electric Winch
6$$	Lift
7$$	Work Environment

Further attributes can also be present depending on the requirement group for example. These are defined in Table 10.

Table 10: Description of requirement attributes

Attribute name	**Attribute description**
Further Description	Normally used for defining broad terms used in the requirement name
Owner	It is the stakeholder the demanded this requirement
Priority	In a project development overview, it indicates which requirement shall be achieved and tested firstly. The lowest the number, the highest the priority
Derived from	It indicates the higher level requirements that originated the derived requirement
Sub-Requirements	It shows requirements that are contained inside another bigger and wider requirement, yet belonging to the same layer

Stakeholder requirements

SHR001 The test bench shall be able to verify new software modules using the W3C box.
Owner: Marine & Offshore

Priority: 1

SHR002 The test bench shall be able to verify new software modules using the RC28 box.
Owner: Marine & Offshore

Priority: 1

SHR003 The test bench shall be able to run while using a hydraulic winch with primary control as motion source.
Owner: Marine & Offshore

Priority: 1

SHR004 The test bench shall be able to run while using a hydraulic winch with secondary control as motion source.
Owner: Secondary Control

Priority: 2

SHR005 The test bench's external communication shall be configurable to match to the client's controller.
Owner: Marine & Offshore

Priority: 2

SHR006 The test bench shall be able to run while using a linear cylinder as motion source.
Owner: Stage Technology

Priority: 2

SHR007 The test bench shall be able to be used for pre-commissioning of new projects.
Owner: Marine & Offshore + Secondary Control

Priority: 3

SHR008 The test bench shall be able to run while using an electric winch as motion source.
Owner: Marine & Offshore

Priority: 4

System Requirements

In order to start the definition of system requirements, the system is first modelled. The Figure 52 provides a visual background for the understanding of the requirements. Moreover, it also defines certain terms to be consistently used across the document. The modelled system is divided into three layers:

A. The **Actuators** contains the system actuators and sensors, e.g. the winches.
B. The **Control Unit** is responsible for gathering all the electric signals from the Actuators layers and serve as an interface to the test objects. It may also contain certain software functionalities.
C. The **Test objects** are attachable controls that use the test bench to verify its software and electric interface.

In this model, the layer Actuators also represents the working area perimeter. This is a physical delimitation of the space where the machinery is located. The requirements related to this perimeter belong to the sub-system called Work environment.

Each layer contains grey boxes – which in turn speak for sub-systems – and arrows, which represent the connections between the sub-systems. Each arrow color can express three different dependencies, as described in the legend.

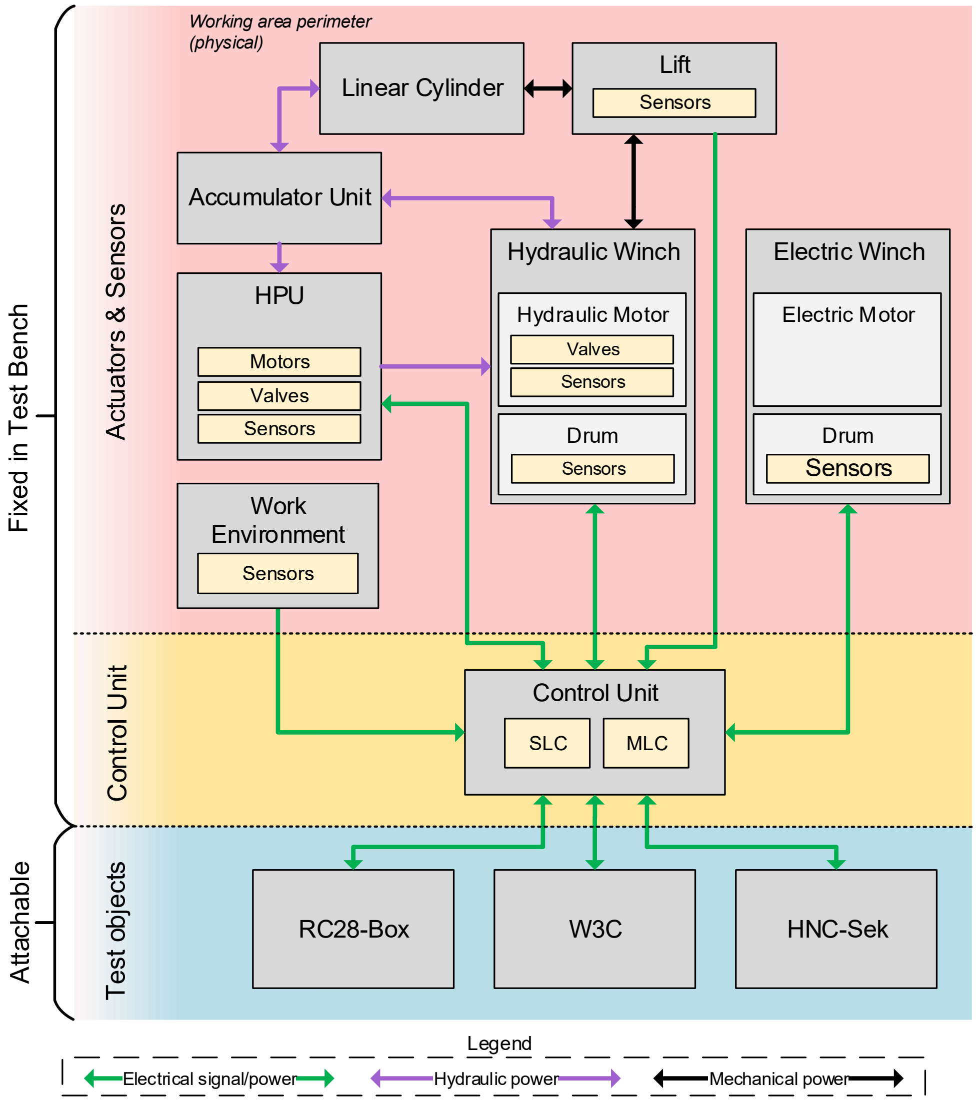

Figure 52: Identification of the sub-systems within the system

The next chapters detail each sub-system and its requirements. However, since the linear cylinder does not belong to the scope of winch systems, its specification is ignored. The test objects are also elsewhere defined, as they are complete products independently of the integration realized in this project. Once they are connected to the bench, it is attempted to take advantage of as many resources as possible, although it is not possible to test all capabilities. The embraced artifices are graphically allocated in Figure 53.

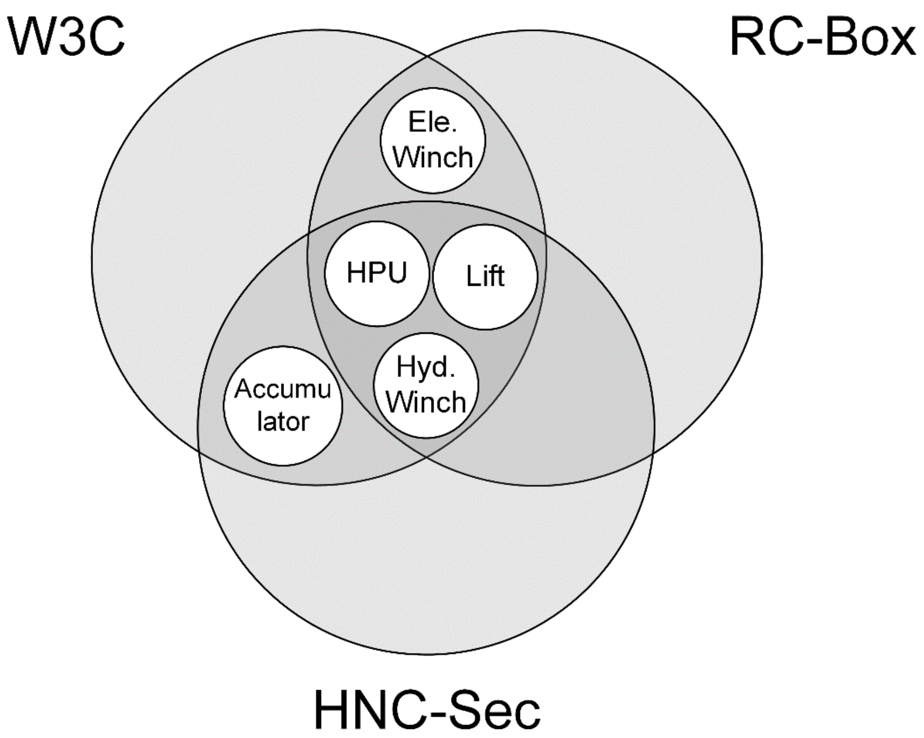

Figure 53: Allocation of features among the test objects

SYR001 The hydraulic winch shall be able to use the lift.
Derived from: SHR001 SHR005 SHR007

SYR002 The electric winch shall be able to use the lift.
Derived from: SHR005 SHR007 SHR008

SYR003 The linear cylinder shall be able to use the lift.
Derived from: SHR006

SYR004 The HPU shall be able to pressurize the accumulator unit.
Derived from: SHR001 SHR004 SHR006

SYR005 The accumulator unit shall be able to supply pressure to the linear cylinder.
Derived from: SHR006

SYR006 The linear cylinder shall be able to supply pressure to the accumulator unit.
Derived from: SHR006

SYR007 The accumulator unit shall be able to supply pressure to the hydraulic winch.
Derived from: SHR004

SYR008 The hydraulic winch shall be able to supply pressure to the accumulator unit.

Derived from: SHR004

SYR009 The HPU shall be able to supply pressure to the hydraulic motor.
Derived from: SHR001 SHR002 SHR003 SHR004

SYR010 The HPU shall be able to supply pressure to the hydraulic brake of the hydraulic winch.
Derived from: SHR001 SHR002 SHR003 SHR004

SYR011 The working area perimeter shall be surrounded by wall, fences or doors.
Derived from:

SYR012 The control unit shall be able to control the electric winch.
Derived from: SHR005 SHR007 SHR008

SYR013 The control unit shall be able to control the HPU.
Derived from: SHR001 SHR002 SHR006 SHR007

Sub-Requirements:

- I. The control unit shall be able to control the supplied pressure.
- II. The control unit shall be able to control the supplied flow.
- III. The control unit shall be able to monitor HPU sensors.

SYR014 The control unit shall interface to the test objects.
Derived from: SHR001 SHR002 SHR003 SHR004 SHR005 SHR007

Sub-Requirements:

- I. The control unit shall interface to the RC-Box.
- II. The control unit shall interface to the W3C.
- III. The control unit shall interface to the HNC.

SYR015 The control unit shall be able to stop the system if a dangerous situation is detected.
Derived from: SHR001 SHR002 SHR003 SHR006 SHR008

Further Description: A situation is considered dangerous if damage to the system or injuries to a person are expected.

Sub-Requirements:

- I. The control unit shall stop the system if an emergency button is pressed.
- II. The control unit shall stop the system if the working area perimeter is crossed (one of the doors is opened).
- III. The control unit shall stop the system if safely related sensors are triggered.

Sub-system Requirements

Sub-system: Control Unit

This sub-system serves as an interface between the connected test objects and all electric devices of the testing bench. It also executes certain functionalities that are not included in the test objects.

SSR101 The MLC shall be able to control and monitor the basic functions of the HPU.

Sub-Requirements:

I. The control unit shall activate the HPU under a command received from the test objects or an HMI.
II. The control unit shall be able to start the pilot pump.
III. The control unit shall be able to start the boost pump.
IV. The control unit shall be able to start the cooling fan.
V. The control unit shall stop the HPU if the ball valves are not correctly set.

Further Description: As the HPU is to serve multiple applications, provisions to manually configure the HPU using stopcock valves are installed. Each operation mode requires a specific disposition of the valves that shall match the Table 11: Configuration of HPU manual operated valves.

Table 11: Configuration of HPU manual operated valves

ID	Name	Description	Default	Acc. Press	PAHC	RAHC
X1	Pilot pressure	Optional pilot pressure connection	Closed			
Y1	Pilot return	Optional pilot pressure connection	Closed			
P1	Accumulator pressure	Connection to B port of main pump		Open	Closed	Open
P2	Auxiliary pressure WRDU	Connection to B port of main pump for WRDU		Closed	Closed	Closed
P3	Auxiliary pressure Bremse	Connection to B port of main pump for Brake		Closed	Closed	Closed
T1	Auxiliary return	Optional return line connection	Closed			
A	Main pump A port	Allows flow to winch motor A port.	Closed		Open	Open
B	Main pump B port	Allows flow to winch motor B port.	Closed		Open	Open
Acc. A	Accumulator in A port of main pump	Additional small accumulator in the pump port	Closed		Closed	Open
Bypass	Check valve bypass in B	Allows return flow to main pump B port.			Open	Closed

VI. The control unit shall stop the HPU if the tank level is below a predefined threshold[7] for more than 1 second.
VII. The control unit shall activate the cooler of the HPU if the temperature of at least one of the temperature sensors reaches 50 degrees Celsius for more than 5 seconds.

VIII. The control unit shall stop the HPU if the temperature of the reading of at least one of the temperature sensors is below a predefined threshold[7] for more than 5 seconds.

IX. The control unit shall stop the HPU if the temperature of the reading of at least one of the temperature sensors is above 70 degrees Celsius for more than 5 seconds.

X. The control unit shall stop the HPU if the return filter is clogged for more than 30 seconds while the temperature before the cooler is above 30 degrees Celsius.

XI. The control unit shall stop the HPU if the pilot pressure filter is clogged for more than 30 seconds while the temperature before the cooler is above 30 degrees Celsius.

SSR102 The MLC shall be able to control the main pump to pressurize the accumulator unit.

Sub-Requirements:

I. The pressure set shall be between a predefined range[7].

II. The pump shall be activated using an on-off control with hysteresis.

III. The desired pressure shall be set by the user through an HMI.

IV. The hysteresis parameters shall be set by the user through an HMI.

SSR103 The MLC shall be able to control the main pump to supply constant pressure to the hydraulic motor.

Sub-Requirements:

I. The desired pressure shall be set by the connected test object.

II. The pressure set shall be between a predefined range[7].

SSR104 The control unit shall be able to allow the control of the swivel angle of the hydraulic pump by the connected test object.

Further Description: In this mode of operation, the control unit serves just as an interface between the connected test object and the swivel angle valve and encoder.

SSR105 The control unit shall have an interface (HMI) to the test bench operator.

Sub-Requirements:

I. The HMI shall have a touch-screen.

SSR106 The MLC shall stop the hydraulic winch if its drum is empty.

SSR107 The MLC shall stop the hydraulic winch if its drum is full.

SSR108 The MLC shall stop the electric winch if its drum is empty.

SSR109 The MLC shall stop the electric winch if its drum is full.

SSR110 The control unit shall be able to control the electric winch.

SSR111 The SLC shall shut down the test bench if any emergency button is pressed.

Further Description: A number of Emergency Stop buttons are installed at strategic locations around the test bench as well as on panels and cabinets. Their locations are indicated in the Figure 60. Each function is described in Table 12.

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[7] Value to be defined

Table 12: List of emergency buttons

E-Stop buttons	Action	Remark
E-Stop ground floor fence	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C
E-Stop base floor fence	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C
E-Stop Mobilmaster	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C
E-Stop on existing operator panel LOP	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C
E-Stop on operator panel LOP HY winch	Delayed shut down	SLC in W3C interlocks with E-Stop circuit of MCC
E-Stop on operator panel LOP EL winch	Delayed shut down	SLC in W3C interlocks with E-Stop circuit of MCC
E-Stop on existing operator panel LOP	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C
E-Stop on MCC	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C

SSR112 The SLC shall stop the test bench if any door of the machinery perimeter is opened.

Further Description: The test arrangement is surrounded by fences and access to the test bench is only possible via doors indicated in Figure 60 and Figure 61. Their functions are described in Table 13.

Table 13: List of monitored doors

Safety Interlocks	Action	Remark
Ground floor door 1	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C
Ground floor door 2	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C
Base floor door	Immediate shut down	SLC in MCC interlocks with E-Stop circuit of W3C

SSR113 The SLC shall stop the test bench if the lift has reached its highest position (refer to Figure 59).

SSR114 The SLC shall stop the test bench if the lift has reached its lowest position (refer to Figure 59).

Further Description: The lowest position allowed to the load is not when it touches the floor, but when the anti-slack device reaches its end position and consequently loses its functionality.

SSR115 The control unit shall be able to control the brake of the hydraulic winch.

Sub-system: Hydraulic Power Unit (HPU)

This project already held a hydraulic schematic of the installed hydraulic power unit and winch. Therefore, it can be used as the sub-system model in order to generate the requirements list. Yet, because of the degree of details engineered internally in the company, is not revealed in this document.

SSR201 The tank level shall be measurable.

SSR202 The tank temperature shall be measurable.

SSR203 The tank oil shall be able to be cooled with a cooling fan.

SSR204 The temperature of the cooler input pipe shall be measurable.

SSR205 The temperature of the cooler output pipe shall be measurable.

SSR206 The cooler line shall be filtered.

SSR207 The status of the filter of the cooler line shall be measurable.

SSR208 The temperature of the main pump input pipe shall be measurable.

SSR209 The temperature of the main pump output shall be measurable.

SSR210 The main pump line shall be filtered.

SSR211 The status of the filter of the main pump line shall be measurable.

SSR212 The pilot pump shall be able to supply hydraulic pressure to the brake of the hydraulic winch.

SSR213 The main pump shall be able to be connected to the accumulator units.

SSR214 The speed of the main pump shall be controllable.

SSR215 The swivel angle of the main pump shall be controllable.

SSR216 The swivel angle of the main pump shall be measurable.

Sub-system: Accumulator Unit

The sub-system called accumulator unit is composed of 4 identical smaller hydraulic accumulators that are connected in parallel, as shown in the circuit of Figure 54.

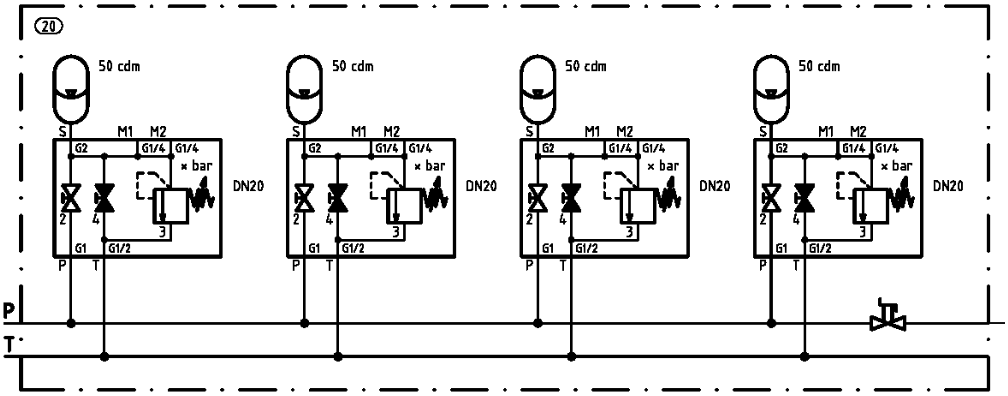

Figure 54: Snapshot of the accumulator unit taken from the hydraulic circuit (Source: Bosch Rexroth)

SSR301 The sub-system accumulator unit shall be able to store and release hydraulic pressure.

SSR302 The sub-system accumulator unit shall be able to be pressurized through one single pipe.

SSR303 The sub-system accumulator unit shall be able to supply pressure to the linear cylinder.

SSR304 The sub-system accumulator unit shall be able to supply pressure to the hydraulic winch.

SSR305 The sub-system accumulator unit shall be able to be connected and disconnected from the external hydraulic supply or load.

SSR306 Each accumulator cylinder shall be able to be independently connected and disconnected.

Sub-system: Hydraulic Winch

The hydraulic winch is powered by the pump located in the HPU and controlled through a series of valves. The Figure 55 shows this circuit and indicates the relevant components.

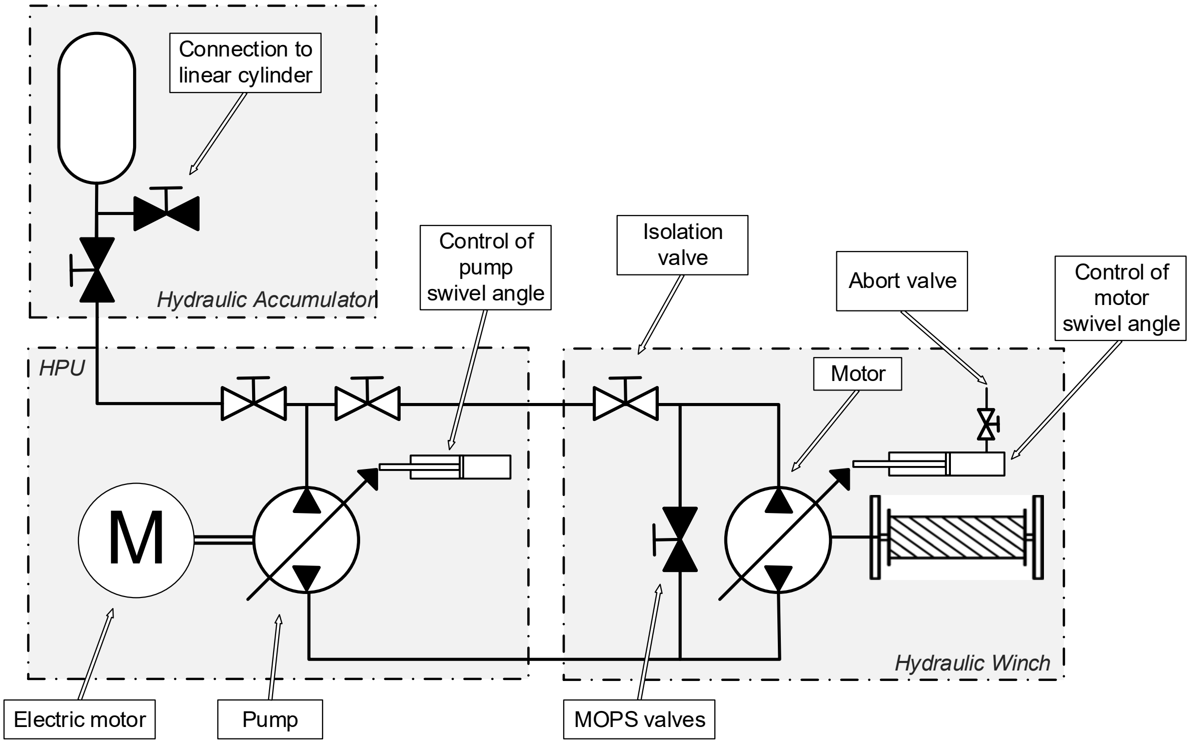

Figure 55: Hydraulic model of the hydraulic winch and periphery with exclusion of electric devices

SSR401 The hydraulic winch shall be able to pull the lift cable.

SSR402 The hydraulic winch shall be able to be stopped by a hydraulic brake.

SSR403 The hydraulic winch shall support MOPS.

Further Description: MOPS stands for Manual Overload Protection Mode. It means that the motor axis can run freely just by applying external torque.

SSR404 The lines between the hydraulic pump and the hydraulic motor shall be able to be isolated.

Further Description: The term 'isolated' means that there will be no flow in this closed circuit.

SSR405 The differential pressure between the input and the output of the hydraulic motor shall be measurable.

SSR406 The swivel angle of the hydraulic motor shall be measurable.

SSR407 The swivel angle of the hydraulic motor shall be controllable.

SSR408 The swivel angle command of the hydraulic motor shall be able to be aborted.

Further Description: If the swivel angle control is aborted by means of an additional switch valve, it returns to the default position. The default position is the maximum angle, that is, the angle that produces the highest torque between the motor and the drum.

SSR409 The speed of the hydraulic motor shall be measurable.

SSR410 The speed of the hydraulic winch drum shall be measurable.

SSR411 The position of the hydraulic winch drum shall be measurable.

Further Description: The position can be measured with a rotary encoder and additionally detected with a gearbox with switches, in case the drum is empty or full.

Sub-system: Electric Winch

Due to the low priority given by the stakeholders, the definition of the electric winch was not established by the time this document was written. Therefore, the requirements following written do not fully represent this sub-system.

SSR501 The electric winch shall be able to pull the lift cable.

SSR502 The electric winch shall be able to be stopped by an electric brake.

SSR503 The speed of the electric motor shall be able to be controllable.

SSR504 The speed of the electric motor shall be able to be measurable.

SSR505 The position of the electric winch drum shall be able to be measurable.

Further Description: The position can be measured with a rotary encoder and additionally detected with a gearbox with switches, in case the drum is empty or full.

SSR506 The speed of the electric winch drum shall be able to be measurable.

Sub-system: Lift

The lift frame contains a load which is raised by means of a cable that can be connected to external actuators, such as the winches and the linear cylinder. The two scenarios are illustrated by the Figure 58 and Figure 57.

To avoid the escape of the rope out of the pulleys, it is also installed an anti-slack protection, as detailed in Figure 56. This plays a role when the load lowers slower than the actuators slewing velocity. An implicit example is when the cable is further released while the load is already laid on the floor.

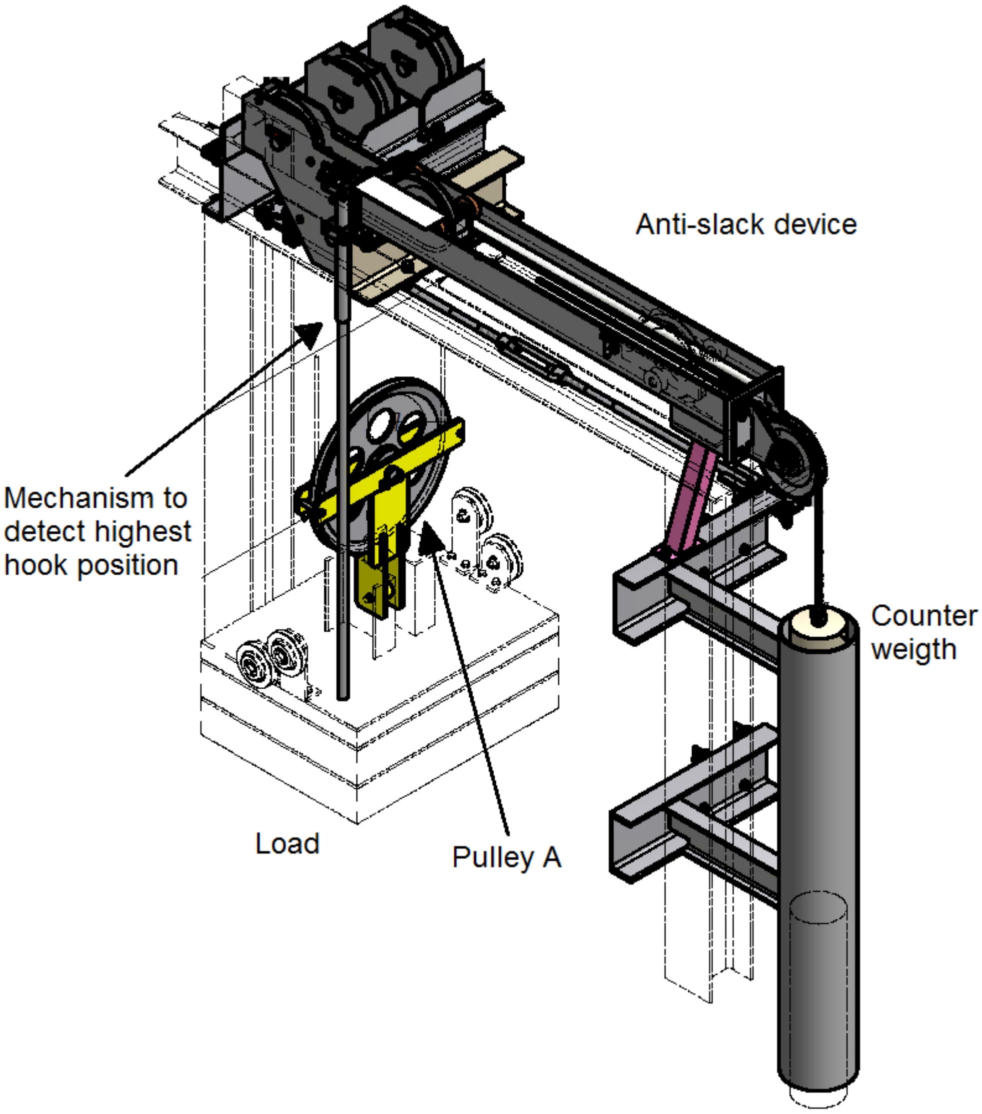

Figure 56: Descriptive geometry of the lift and its anti-slack device (adapted from Bosch Rexroth)

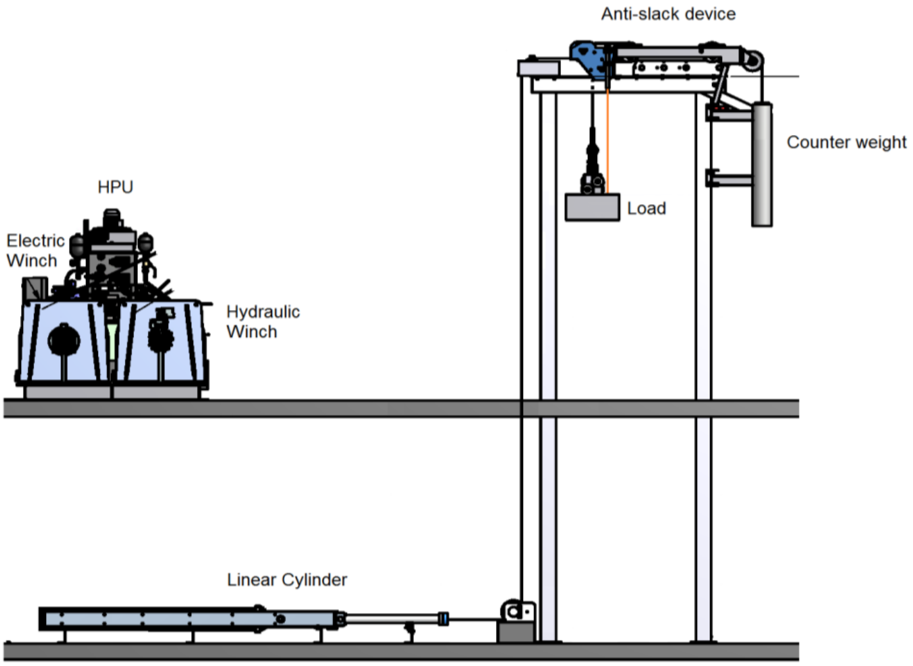

Figure 57: Lateral view of the lift connected to the linear cylinder (adapted from Bosch Rexroth)

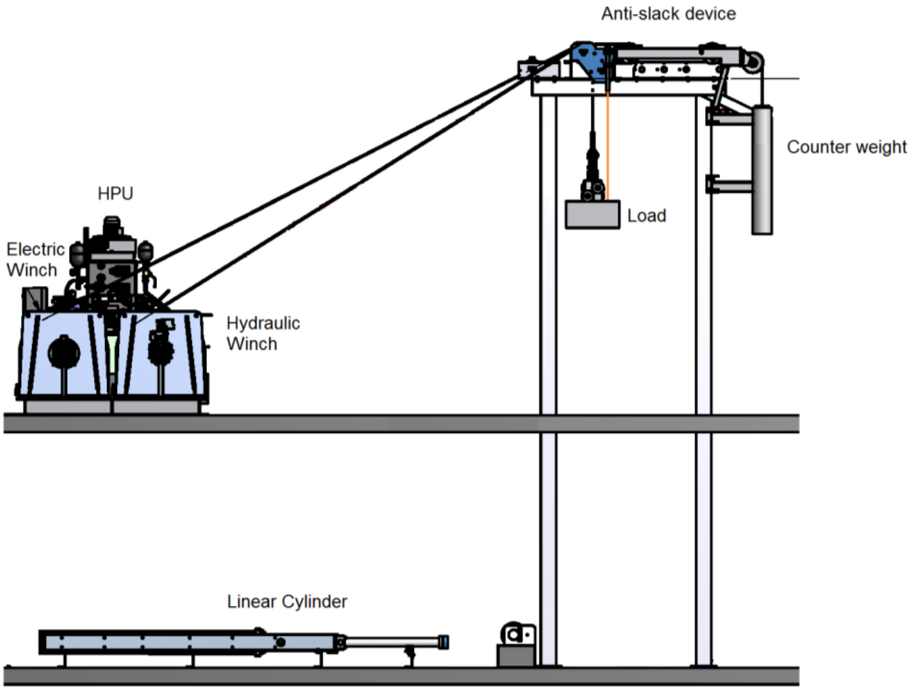

Figure 58: Lateral view of the lift connected to the winches (adapted from Bosch Rexroth)

When connected to both winches, the sheave indicated in Figure 56 as "Pulley A" allows the drums to rotate independently of each other. The cable routing is also shown in the Figure 59 together with all sensors installed.

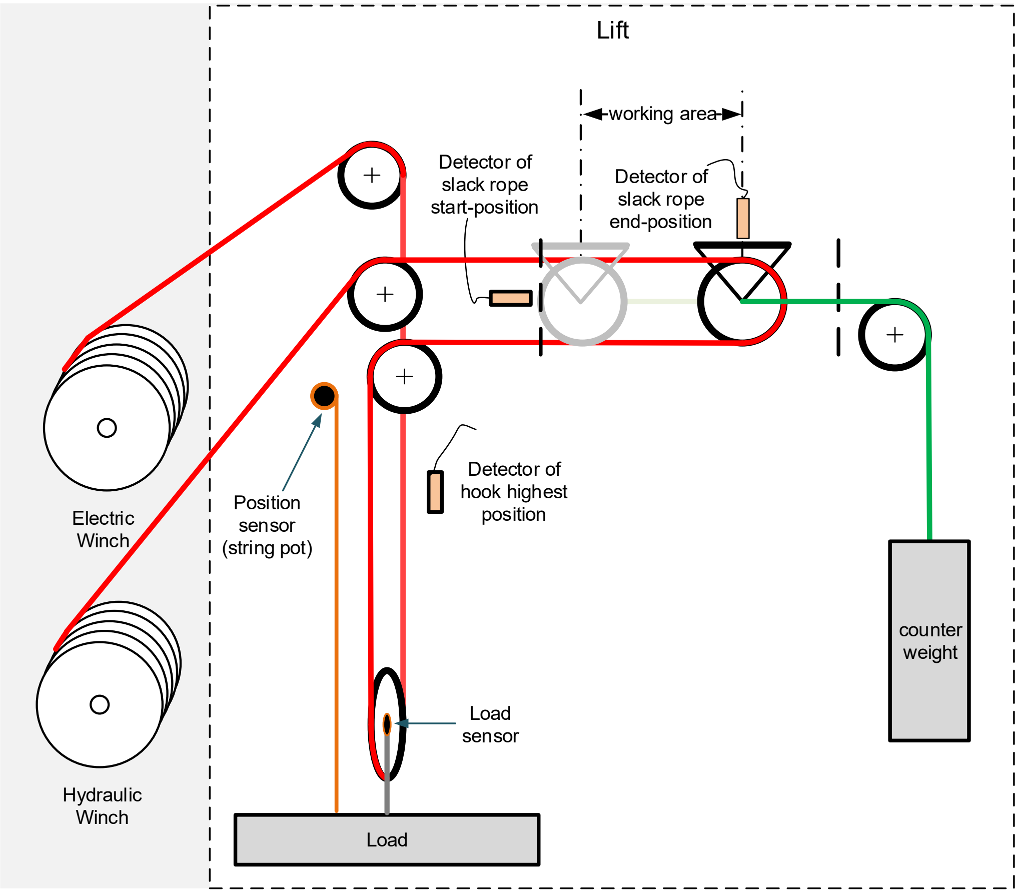

Figure 59: Sensors and mechanisms installed on the lift

SSR601 The position of the load shall be measurable.

SSR602 The pulling force of the load shall be measurable.

SSR603 The load cable shall have an anti-slack protection.

Sub-Requirements:

I. The anti-slack protection shall keep a tension force between XXX and XXX N.
II. The anti-slack protection shall keep the tension force for at least XXX mm of displacement.

SSR604 The position of anti-slack device shall be detectable with limit switches.

SSR605 The load shall be replaceable.

SSR606 The load shall be able to be simultaneously supported by the hydraulic winch and the electric winch.

SSR607 The load shall be able to be connected to the winches or to the linear cylinder.

Sub-Requirements:

I. The operation to switch between the two pulling sources shall take not more than one day.
II. This operation to switch between the two pulling sources shall be documented.

Sub-system: Work Environment

The sub-system work environment defines the boundary of the machinery, including its doors and the emergency buttons attached. For that purpose, the Figure 60 and Figure 61 show the other sub-systems enclosed by fences and three doors, two on the ground level and one underground. Both door switches and emergency buttons are normally closed contacts (NC).

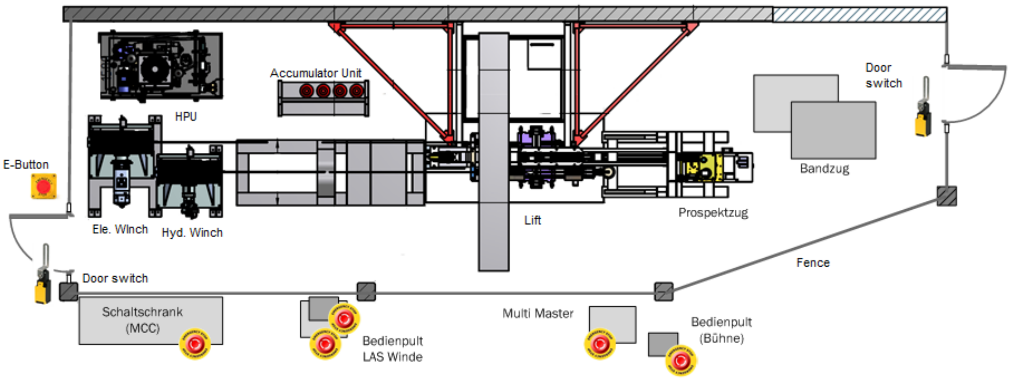

Figure 60: Work environment (upper view) (adapted from Bosch Rexroth)

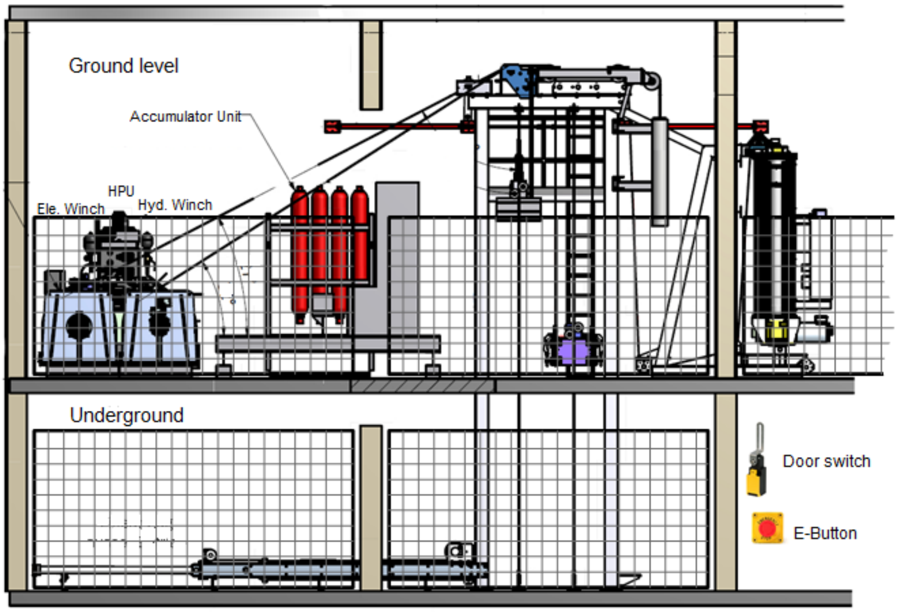

Figure 61: Work environment (lateral view) (adapted from Bosch Rexroth)

SSR701 The position of each door of the machinery perimeter shall be measurable with a position switch.