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Mathematical Sciences and Technology

Chassis Modular Design and Electrical Layout for the NMBU Agricultural Robot Project

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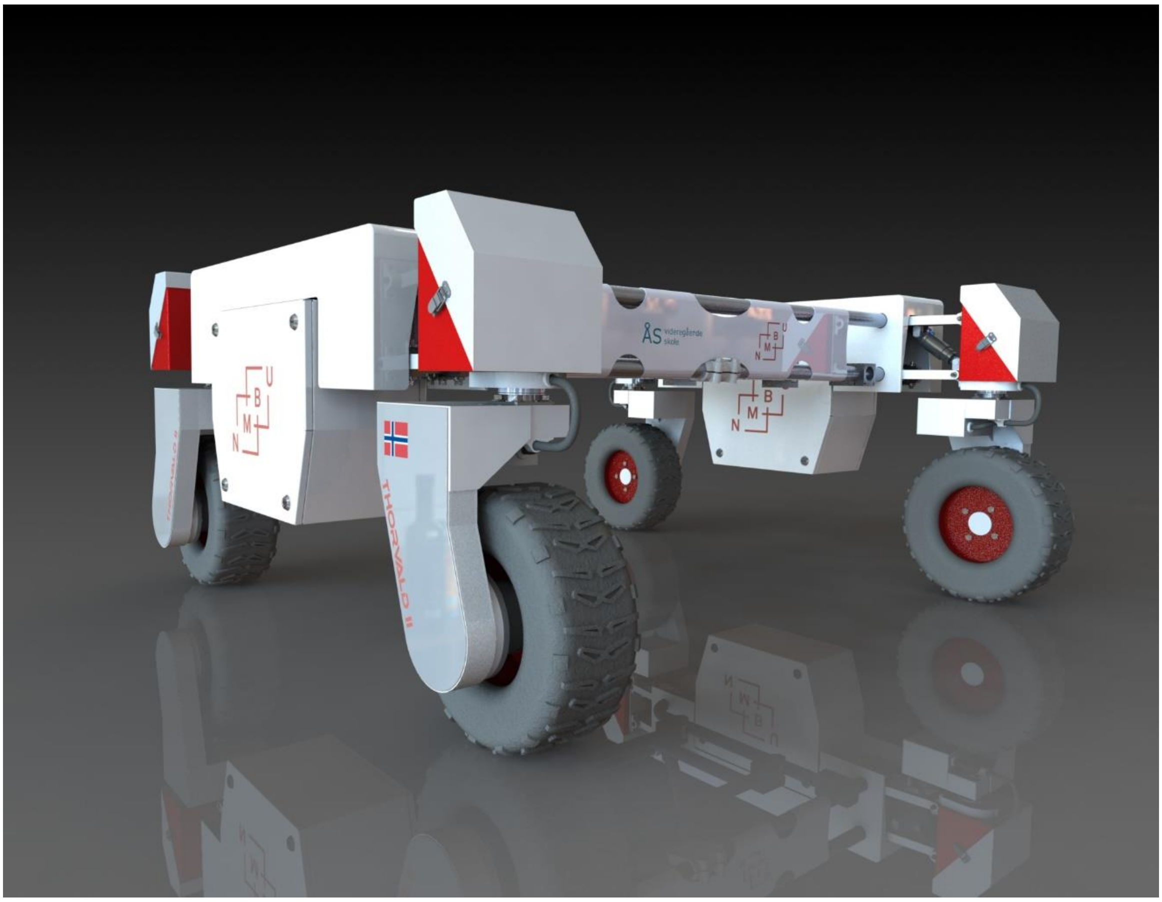
THORVALD II

Preface

I have my background from the aviation industry as an aircraft mechanic in the Scandinavian Airline Services, and started a master study at the Norwegian University of Life Sciences.

My first thoughts about robot development had premature assumptions of advanced programming and complex control systems. So my choice of a robotic master thesis was initially a bit scary. I soon realized that all robots also require a sturdy frame and mechanical innovations that software systems depend on, and not the other way around. Hard working robot engineers often lack the resources of mechanical engineering and end up with simple robots. After learning about basic robotics manipulator systems I felt more confident about this choice.

As a result, my enthusiastic robotic team and I ended up in Brazil to learn more about agriculture and robotics. We visited a Norwegian company called UMOE Bioenergy that utilize large fields on the countryside to grow sugar canes for the production of bio fuel. Here we learned about the functions of different vehicles and their automation, as well as the entire production process. During a visit to the Federal University of Rio de Janeiro (UFRJ), we were introduced to their robot program and their ongoing research and development projects. This trip allowed us to present our project and exchange ideas and experiences. The trip also allowed us to bring the whole team together and exchange ideas and help each other.

Using my previous experiences, the development of the new robot platform involved countless hours of searching for modular solutions. None of the systems were entirely what I was looking for, and I don’t like compromises or tradeoffs. I ended up developing my own ideas inspired by different modular concepts that evolved for every version I was sketching or modelling. In the end I found the solution I was looking for, which allowed extreme flexibility, easy modification or equipment retrofit without welding. My advisor commented that he has not seen anything similar to this untraditional concept in the robot industry before.

I would like to personally thank Knut Karlsen at UMOE Bioenergy for taking me and my team around the sugarcane fields in Brazil for days and teaching us about the processes. I would also to thank the robotic team of UFRJ for informational exchange and the CAPES-SIU project for covering our traveling expenses. I would like to thank Amatec, Stena Stål Moss, and Elfa Distrelec for discounted components and materials. I would like to thank Jan Wilhelmsen at Dynatec SMV for the use of a water cutting machine free of charge. I would like to thank Tom Ringstad, Geir Taxt Terjesen, Petter Heyerdahl, and Tore Ensby for advice and creative discussions around the project. I also want to thank the studentss and their teachers, Endre Grøtvik, Rune Stensrud and Øyvind Hansen for the collaboration with Ås High School for production of parts and the apprentice, Bjørn Tenge, at the NMBU workshop.

I also especially want to thank my advisor Pål Johan From, my family, the robotics team and fellow students Marius Austad, Alexander Tekle, Espen Ovik and research fellow, Lars Grimstad, and "Eik Ideverksted" for support and advice.

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Sammendrag

Denne masteroppgaven består av to deler, hvorav del en består av design av ramme for den mobile plattformen, samt en beskyttende kasse for batteri, elektronikk og elektrisk system. Del to består av design av det elektriske systemet, med tilhørende design og oppsett av nødvendige elektroniske komponenter.

Del én

Formålet med del en av denne masteroppgaven er å designe en ramme til en robot som skal klargjøres for leveranse ut til markedet. Dette innebærer å øke skalaen for produktets modenhetsnivå til minimum åtte av ni mulige. Dette prosjektet er en videreutvikling av prototypen vår, Thorvald 1. Målet for oppgaven er å promotere vårt bidrag til FNs klimarapport som informerer om at kun små endringer skal til for å endre utslippene fra jordbruket drastisk. Dette innebærer å lage lette robotiserte kjøretøy som unngår pakking av jorden. Roboten bør være enkel å konfigurere i forhold til tilgjengelig verktøy og behov. Arbeidet mitt har hittil bestått i å studere ulike konstruksjonsmetoder, materialer, modulære konsepter og enkle produksjonsmetoder for å kunne lage en modulær ramme basert på krav som er oppgitt. Jeg endte opp med å lage en stiv dobbel ramme av aluminiumsrør med enkel rekonfigurering. Beholderen som inneholder elektronikken ble designet av knekte aluminiumsplater, forseglet med en gummipakning.

Del to

Dette er den elektriske og elektroniske delen av masteroppgaven. Ved å analysere ulike spesifikasjoner for forsegling av elektriske komponenter, datamaskiner, tilbehør, dataprotokoller, samt oppstartssekvenser og elektroniske komponenter, har jeg gjort en rekke nødvendige valg. Alt dette for å sørge for en trygg velfungerende robot. Valget av datamaskin falt på en NVidia Jetson basert plattform som er utviklet for robotprosessering og maskinsyn. For styring av oppstartssekvensen har jeg designet et elektroniskkretskort som kan masseproduseres. Siden roboten enda ikke har blitt bygget, planlegges det at gjenstående sammenstilling av elektrisk system blir gjort i løpet av de neste ukene.
Hvis mitt arbeid viser seg vellykket innen masterforsvaringen, har prosjektets modenhetsnivå blitt økt til nivå åtte. I tillegg har jeg da bidratt til en ny form for lavbudsjett design innen robotutvikling. Ved videre testing og forbedringer vil vi kunne nå siste ledd av modenhetsskalaen.

Abstract

This master thesis is divided into two different parts. Part one consists of the design of a chassis frame and an environmentally protected electronics compartment. Part two consists of the design and choice of the necessary components for the electrical power system and system configuration.

Part One

The purpose of part one of this master thesis is to design a frame that is ready for marked and at least a level eight out of nine in Technology Readiness Level. It is a further development of the Thorvald I prototype and the entire Thorvald robotic development process. The mission of this project is to promote our answer to the UN emissions gap report in making small changes for the global agriculture and to massively reduce the global emissions. This means making a lightweight low cost robot vehicle that reduces soil packing. The robot should be easy to configure according to needs and tools. My work includes analyzing different construction methods, materials, modular concepts and methods of manufacture to be able to create a modular frame, based on previously set requirements. I ended up with a rigid double tube based frame with an easy changeable configuration. The electronic compartment was made out of press formed aluminum, environmentally sealed with a rubber gasket.

Part Two

This is the electrical and electronic part of the master thesis. By analyzing waterproofing theory, computer systems, communications and accessories, power-up sequencing systems for batteries and the electrical system, I have made suitable choices with the electrical and electronic designs and suggestions to make a safe, well-functioning robot. The choice of computer fell on the NVidia Jetson based platform, especially designed for robotics and machine vision. For controlling the startup procedure I have successfully designed and built an electronic printed circuit board that is suitable for mass production. Since the robot has not yet been built, remaining assembly and electrical harnessing will be done during the next few weeks.

If my work proves successful and reaches TRL9 within the Master thesis defense, I have contributed in a low-cost modular robotic design that can be used freely by everyone who wishes to contribute in closing the gap towards the 2°C climate goal.

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Symbols and Abbreviations

Table 0-1. Symbols and description

	Symbol	*Designation*	*Abbreviation*
Length	L, l	Millimeter	mm
Area	A	Millimeter^2	mm^2
Force	F	Kilogram	kg
Weight	m	Newton	N
Moment	M	Newton meter	Nm
Tension and Compression Stress	σ	Mega pascal	MPa
Shear Stress	τ	Mega pascal	MPa
Second Moment of Inertia	I	Millimeter^4	mm^4
Section Modulus	W	Millimeter^3	mm^3
Elastic Modulus	E	Mega Pascal	MPa
Shear Modulus	G	Mega Pascal	MPa
Poisson's Ratio	ν	-	-
Efficiency		Percent	%
Friction Coefficient		-	-
Diameter	D, d	Millimeter	mm
Equivalent dynamic load	P	Newton	N
Memory	-	byte	B
Voltage	U	Volt	V
Current	I	Ampere	A
Resistance	R	Ohm	Ω
Power	P	Watt	W

IPCC	Ingovernmental Panel of Climate Change
NASA	National Aeronautics Space Agency
SI	Système International
PLA	Polylactic Acid
HSE	Health and Safety at Work
ISO	International Organization for Standardization
NOK	Norwegian Kroner (currency)
CPU	Central Processing Unit
RAM	Random Access Memory
FLOPS	Floating-point Operations per Second
CAN	Controller Area Network
LAN	Local Area Network
USB	Universal Serial Bus
BMS	Battery Management System
NO	Normally Open
SSR	Solid State Relay
NPN	Not Pointing iN
HDMI	High Definition Multimedia Interface
PCB	Printed Circuit Board
QUT	Queensland University of Technology
TRL	Technology Readiness Level
ABS	Acrylonitrile Butadiene Styrene
CNC	Computer Numerical Control
VF	Vehicle Factor
FEM	Finite Element Method
USD	US Dollars (currency)
GPU	Graphics Processing Unit
DC	Direct Current
UAV	Unmanned Aerial Vehicle
ROS	Robot Operating System
WAN	Wide Area Network
PLC	Programmable Logic Controller
I2C	Inter-Integrated Circuit
NC	Normally Closed
FET	Field Effect Transistor
PNP	Pointing iN Permanently
AWG	American Wire Gauge
ESD	Electrostatic Discharge

Formulas

Table 0-2. List of Formulas

Number	*Formula*	*Description*
(2.1)	$F = -kX$	Hooke's Law
(2.2)	$K = \frac{1}{2}mv^2$	Kinetic Energy
(3.3)	$Specific\ Strenght = \frac{Tensile\ Strength}{Specific\ Weight}$	Specific Strength
(5.4)	$F_N = \frac{m \cdot g \cdot VF}{4}$	Wheel Normal Force
(5.5)	$T_{w,max} = T_{m,max} \cdot i_G \cdot i_B \cdot \eta_G \cdot \eta_B$	Wheel Torque
(5.6)	$F_p = \mu_k \cdot N$	Propulsion
(5.7)	$T_{w,req} = r_w \cdot F_p$	Required Wheel Torque
(5.8)	$\Sigma M = 0$	Newton's 3. Law of Moments
(5.9)	$\Sigma F = 0$	Newton's 3. Law of Forces
(5.10)	$tan\ \alpha = \frac{Opposite}{Adjacent}$	Right Triangle Law
(5.11)	$V_2 = \frac{F_p}{4} = 0.25\ F_p$	Shear Vector
(5.12)	$\mathrm{V_R} = \sqrt{\mathrm{V_{1y}}^2 + (\mathrm{V_{1x}} + \mathrm{V_2})^2}$	Vector Resultant
(5.13)	$\tan \beta = \frac{\mathrm{Opposite}}{\mathrm{Adjacent}}$	Right Triangle Law
(5.14)	$\mathrm{F_i} = \frac{\mathrm{F} \cdot \mathrm{n_g}}{\mathrm{n} \cdot \mathrm{m} \cdot \mu}$	Bolt Pretension
(5.15)	$\tau = \frac{F}{n \cdot A}$	Bolt Shear Stress
(5.16)	$y = \frac{M(l/2)x}{6EI} \cdot (1 - \frac{x^2}{(l/2)^2})$	Beam Deflection
(5.17)	$\sigma = \frac{M}{W}$	Bending Stress
(9.18)	$U = R \cdot I$	Ohms Law
(11.19)	$W = ((I/(k \cdot (\Delta T)^b))^{1/c})/t$	PCB Trace Width

Contents

1. Introduction

1.1. Background

Due to farmers decreasing salary, farmers are under pressure to produce more food for less work. This includes the use of larger and heavier machinery that compacts the soil. This is despite the efforts of the Norwegian agricultural advisory services, Norsk Landbruksråd [1], to avoid soil packing for both environmental reasons and the potential of increasing the crops.

The Norwegian University of Life Sciences (NMBU) are continuously expanding the research in the field of robotics. This includes development of a lightweight agricultural robot that can virtually avoid soil packing. This project includes the previous development of the Thorvald I prototype. This prototype is somewhat simple in frame design, but still relatively advanced in terms of component as well as showing the potential of the use of robotics in the fields. Thorvald I features 4-wheel drive and 4-wheel steering, using two electrical motors in each wheel set. This opens for advanced movement and reduces the risk of being stuck in the mud. However, there are a few short-comings with the first version, which needs improvement and redesigning before selling to collaborate universities, research centers or so on. Even so, in concept the new version will keep the key features, but there are new demands to consider when designing the upgraded Thorvald II.

1.2. Motivation

Witnessing global changes, man-made climate changes around the world has indeed increased concerns about the global health. Scientists in the UNs Intergovernmental Panel on Climate Change (IPCC) say that the increase of global average temperatures cannot pass two degrees Celsius without huge incontrollable impacts [2].

The Norwegian university of life sciences has during the last few years started the development of an agricultural robotic mobile platform called Thorvald. This platform is made as a stage towards the development of a lightweight autonomous revolution of farming and agriculture. There is a number of problems with farming today, including soil compaction caused by the use of heavy machinery, and the enormous amount of fossil fuels used to correct it during tillage. In according to the UNs emissions gap report [3] it is estimated that a significant amount of the emissions used in agriculture around the world is caused by correction of soil compaction. In a global perspective farming is responsible for about 10% of all climate gas emissions, including carbon dioxide and methane gasses and more. The annual emissions gap report measures the difference between countries pledged climate gas emissions cuts, and the actual targets that is needed to keep global average temperature below 2°C.

In context, if all countries meet their pledge of the 2°C target there is still an emissions excess of 12 Gigatons climate gasses per year to make the target. Estimations suggest that small changes in agriculture is enough to cut two thirds of this remaining gap.

In Norway there is an ongoing discussion about how to manage future farming. One side of the discussion is about how the ecological farming methods is not sustainable enough to supply food for the future massive population on earth. If farmers are to produce appropriate amount of food, they will have to industrialize the agriculture with massive machines and chemicals to maximize the production. New technology is welcome, both machines and chemical anti-weeding, which stands in contrast to the ecological side of the agriculture. The industrialization of the farming methods is however not so obvious. Heavy machinery is destroying the soil by compression, creating non-aerobic conditions in the soil according to Zero report by Hojem & Ohna [4]. These conditions contribute to the production of nitrous oxide, which is a worse climate gas than carbon dioxide. In addition to reduce soil packing, plowing half a meter through the earth is the solutions used in industrialized farming. This task demands an enormous amount of energy, performed by powerful diesel tractors, and resulting in significant carbon emissions.

The other side of the discussion is about producing ecological foods. The idea is about producing in a way that is sustainable in form of preserving the natural biodiversity and biosphere. Reduction in carbon emissions and chemical anti-weeding could among other effects result in weeds and plants evolving resistance. The concerns are reduced growth due to resistant weeds or other pests causing global food crisis.

In the end both forms of farming or agriculture has its pros and cons. We want to produce ecological food, but we can't find a way to produce in a sufficient amount to feed the population in the near future. The solution could be to perform ecological farming in an industrial scale in the way of automation. A swarm of robots could in the future perform much of the same tasks as a farmer could do with a tractor. They would also work 24 hours a day. If a number of robots substitutes one tractor they wouldn't need to be as heavy, which reduces, or eliminates soil packing. This way a farmer won't need heavy machinery to plow the fields, saving a significant amount of fuel per season. These questions or philosophies that show up in debates are not only a local issue, but also a worldwide problem that needs to be solved.

1.3. Existing Concepts

The number of existing concepts is rather sparse compared to the potential of the use of robotics and automation in agriculture. In the near future we will probably see more and more, as automotive systems can show their true potential and the robotic parts and subsystem technology already are getting available for a relatively low cost.
There is however a number of robotic platforms available today; one of them is the Bonirob, created by Robert Bosch Gmbh in cooperation with Amazone werke Gmbh [5]. This platform is a multi-purpose agricultural robotic platform. It has a four-wheel independent steering and drive, and can automatically adjust track width. It can run batteries and extend running time by the use of a generator. The weight of the robot is

about 1100 kg with a payload of 150 kg. The Bonirob works at a speed up to 5.4 km per hour.

Figure 1-1. The BoniRob developed by Bosch GmbH[6].

Other concepts include the QUT AgBot II, which is developed by the Queensland University of Technology in Brisbane [7]. Very few details are available for this platform except a few videos on YouTube, and it is not officially available for purchase as a research platform. Judging by the picture the robot will be a two-wheel drive vehicle with rear caster wheels.

Figure 1-2. The AgBot II developed by QUT in Brisbane[8].

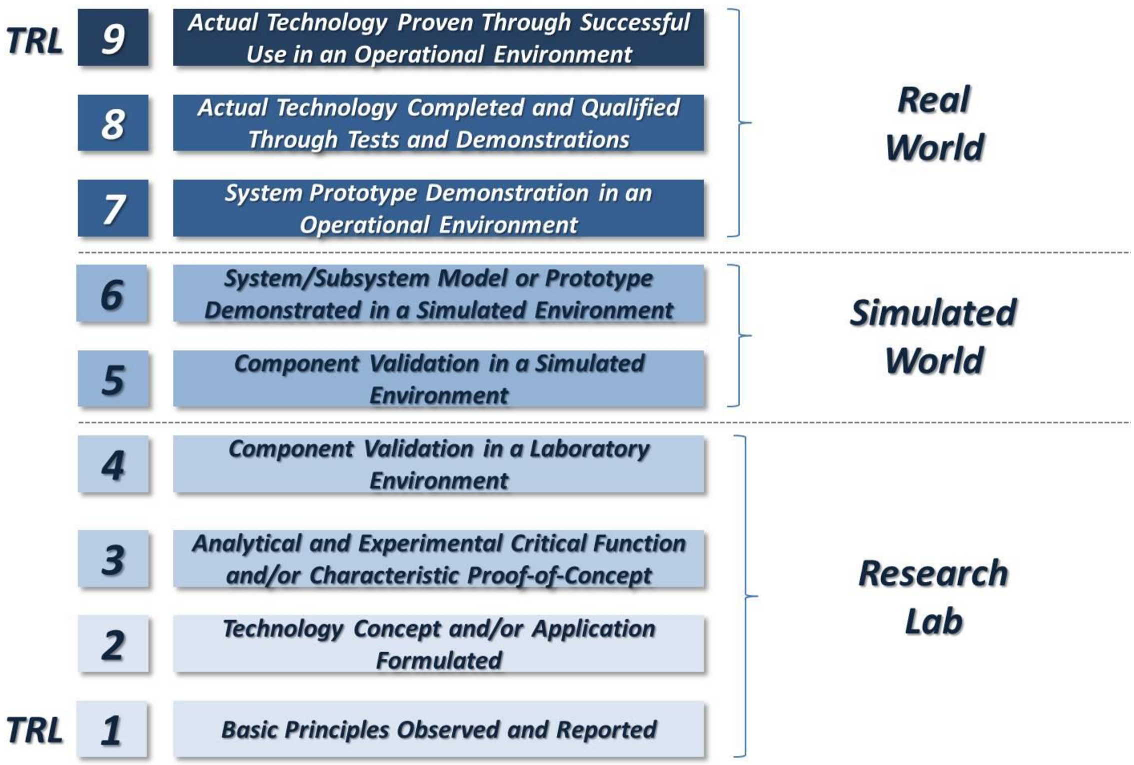
In more familiar grounds, Denmark, Kongskilde industries has made an upgraded version of the Robotti, Robotti II shown in Figure 1-3. There is not much information available yet, but it has the feature of front wheel steering and rear suspension. Its double nacelle design contains both battery systems al electrical motors.

Figure 1-3. The Kongskilde Robotti II.

1.4. Mission Statement

The mission of this master thesis is to participate in the robotics development by designing the necessary main components of the robotic platform. Such components include the design and development of a modular frame, which allows a versatile, easy configuration and modifications for any kind of tasks for individual scientific purposes, and the design of an enclosure that protects and ensures safe storage of batteries and electronics for normal use. The design needs to fulfill the missing factors in the Thorvald I design, and needs to satisfy an industrial standard in terms of durability. The development of a truly hundred percent finished product is a long or even eternal process depending on the complexity of the product. If a product can be nearly finished and ready for the market, only small corrections are necessary to improve further versions. By using a Technology Readiness Level (TRL) -grading system developed by the North American Space Agency (NASA) [9], it is possible to measure the maturity of the technology by the levels in Table 1-1. Thorvald I is graded as a level seven prototype, so if the development of Thorvald II should be of a higher level it needs to be at least qualified through tests and demonstrations at level eight. This level requires the product proven to work in its final form under expected conditions. The requirements of level 9 TRL are actual successful applications in its normal operating environment.

Table 1-1. Chart concisely describing the Technology Readiness Revel, TRL. Thorvald prototype currently is at level 7, while the final version needs to be at least level 8 [10].



1.5. Early Selection of Concept

There are a number of concepts that were considered before final selection of the platform being developed. The concept designs are considered by the following factors.

1. The modularity. The ease of individual configurations for different needs and size.
2. Simplicity. How simple can the platform be in the number of parts, and the ease of manufacture.
3. Durability. The potential of how durable the design can be.
4. Flexibility. The flexibility of the concept by the manner of mounting tools and equipment.
5. Design. The importance of the design and what the concept will look like.

1.6. Requirements and Scope of Thesis

The development team of the new Thorvald II agricultural robot consist of myself and Marius Austad. I am responsible for the frame development and the electronic compartment, including selection of electrical and electronic components. Marius is responsible of the wheel module design within a separate master thesis.

This thesis has the purpose of finding a modular solution for the frame, which enables a wide range of configurations depending on demands. This means contributing to a design that is safe, reliable and sturdy without affecting the flexibility of the system. Second, the platform will need an electronics container with selected contents that is waterproof enough for certain conditions.

The frame and mechanical components need a design that in a way ensures easy access and mechanical simplicity. This so that everyone with moderate or no mechanical skills easily can modify or repair the product in a short amount of time. It should not be necessary to rebuild the entire robot for a reconfiguration.

Thorvald is to be used in relatively dirty and bumpy environments such as driving a whole day in a muddy field on a rainy day. This will cause wear, especially with movable parts and constructions. The low velocity of the product will not by itself cause considerable wear, but together with dirt, water and other particles it needs consideration. As this will be a next generation of the robot I need to increase the Technology Readiness Level compared to the first version.

In the electrical part compatibility is important to take into account as the main contents needs to be select with today's available technology in mind. As modern technology might replace the selected main components, it is necessary to use the newest products available, as well as using well-established standards and flexible connections. This will make it easy to do future changes if applicable.

Most of the programming is already done on Thorvald I, but Thorvald IIs ROS system and some features during the electrical startup procedure needs revision and customization.

The Thesis will include hours of dedicated work and description of the building process, programming, testing and part production.

1.6.1. Problem Formulation

Based on the scope if thesis and mission statement I have stated the following problem formulations:

The main objective is to make a modular, lightweight and a reliable concept for an agricultural robot while keeping mechanical simplicity and at the same time, increase the robot's Technology Readiness Level to at least level eight.

Secondary problems include protection of vulnerable electronics, making the electrical system neat and tidy, selection of components and discuss ideas of necessary accessories to make the robot more versatile in a natural agricultural environment.

Part I

Frame Modular Design and Development

2. Frames and Vehicle Construction

2.1. Non-rigid Frame Design

A non-rigid frame design doesn’t in the first instance seem like a particularly solid idea. But there are a number of advantages if you design in a way that gives you flexibility in the desired directions. If you would like the wheels to flex up and down on an uneven ground, make the moment of area less in the travel direction, and larger in the directions you want rigid. A typical way to solve this is to use a rectangular beam. Thorvald I is constructed with a flexible U-shaped, rectangular frame, and is designed to bend and flex so that all the wheels are touching ground at all times. In other unwanted directions the first robot is more firm with less displacement. This is a very low cost design that gives you the traction needed to get the work done. However, as a modular design, difficulties have appeared in order of making the connections rigid enough. Other problems involve the challenges of installing tools on the robot, as the frame is constantly in movement.

Figure 2-1. Demonstration of Thorvald I with agricultural minister of Norway, Jon Georg Dale, behind the steering stick. Frame flexibility is visible while driving over the wooden pallet.

2.1.1. Beams

Beams are simple constructional elements, often designed in different ways to ensure rigidness in desired directions. They are designed in way that saves material and weight only by using material where it structurally matters, as it is the outer material that stands for most of the rigidness because of the moment of area. The beams can be put together in a way that gives you either a frame, truss or even a flexible structure. Steel beams are usually simple in profile, but some aluminum beams are extruded into advanced profiles that gives you a modular solution and still keep the rigidness.

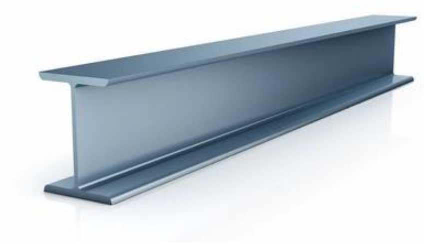


Figure 2-2. Example of an Steel I-beam type[11].

2.2. Frame Design

2.2.1. Truss

Trusses are the most used construction types in modern history. It is a selection of links or bars carefully put together in angles and joined with frictionless joints to ensure axial forces only. This type of construction, depending of complexity, is often designed with hours of statics calculations. Today engineers have more and more help by complex computer processing to solve complex structures. There are, however, some disadvantages in this type of construction. One is that it demands much work and welding or riveting. These constructions are solely used in static structures, and not in dynamic systems such as vehicles.

2.2.2. Space Frame

The space frame is similar to trusses, but instead of frictionless joints, the rod ends are usually welded together to ensure a minimum of weight and materials without compromising the dynamic rigidness. A space frame is subject to axial forces, shear forces and moments. They’re often put together in other geometric figures than triangles as well. For a strong and long lasting welded structure, it is better to use steel as a truss material rather than aluminum; this is because aluminum does not respond well by welding. Welding of aluminum requires the right aluminum alloy, that not necessary gives the best strength aluminum alloys has to offer. There are space frames constructed in aluminum by Audi and other manufactures, which are constructions that usually are riveted together.

Figure 2-3.The Forth Railway bridge in Scotland and The Arial Atom are both well known truss and space frame constructions and used in entirely different contexts[12] [13] .

2.2.3. Semi Monocoque

A semi-monocoque structure is a structure that consists of an outer shell that is reinforced with an inner structure. The main loads are carried by the outside shell, but formers and beams help keeping the shell in the right shape so it doesn`t collapse. This kind of structure has been used by the aircraft industry since the early 1900s, and is about to be replaced by the even lighter monocoque structure.

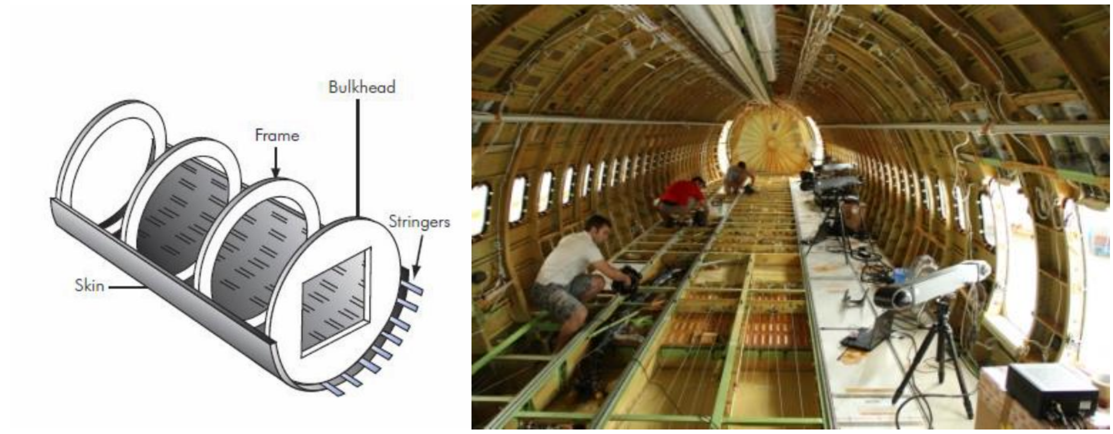


Figure 2-4.Semi-monocoque structure and its components [14] and a Boeing 737 internal structure [15].

2.2.4. Monocoque

A Monocoque structure is a structure that consists only of an outer shell, just like an egg. This is related to the semi-monocoque structure, but without the inner structure. This technology has been developed by the nature since the egg was introduced, but very hard for humans to imitate because of the lack of a strong, lightweight, formable material. Until recent, technology has made it much easier because of the extensive use of composite materials. Composite monocoque is now used in the latest aircrafts, cars, motorcycles and many other products available today.

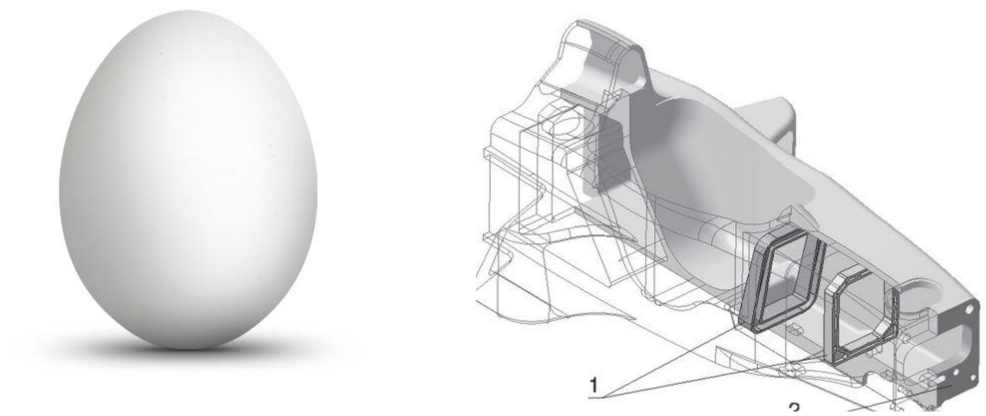


Figure 2-5. Egg and formula 1 car as examples of monocoque structure[16, 17].

2.2.5. Natural Constructions

Many would believe that humans invent most of the constructions used through time in human history. In almost all cases this is completely wrong. The egg is as mentioned an example of natural evolvements, but trusses, space frames, and honeycombs are as well. Nature has slowly developed lightweight structures to reduce the need of energy for creatures, and make the birds able to fly. Therefore, it is important not to forget to look back at nature when looking for solutions, as nature probably already figured it out.

Figure 2-6. Bird bone. Nature's way of construction that reminds of space frame and honeycomb structure [13] [14].

2.3. Vehicle Suspension

Early vehicles dated thousands of years ago, like horse carriages, were made without any form of shock absorbing properties in according to CitroenNet [18]. These carriages were made for the purpose of slow transportation of goods, and did not experience any need of suspension. This was until the horse chariot races of ancient Rome where the high speeds caused unstable and dangerous situations and caused more causalities than gladiator fights in the arenas. To do something about this the Roman Empire was probably one of the first to try a suspension system that resembles the modern day suspensions. These suspensions proved to cause too much wear and allowed only low speeds to be further developed. It wasn't until the 8th century that discovers found that chains and straw baskets were used, and probably caused the travelers seasickness.

The oldest dated discoveries of metal springs are dated to the 17th century. And by the early 1900 every type of materials, shock absorbers and suspensions principles as we know today were being invented, following by the refinements of the world wars.

If the Thorvald II-design results in a rigid frame design there would be need for other forms of movement, so that all the wheels are touching ground at all time. These movements can be conducted by a spring suspension.

2.3.1. Springs

While driving around in the terrain, the suspension continuously adapt the vehicle to uneven challenges to ensure the highest possible performance and best possible weight distribution [19]. When the vehicles suspension has overcome its work, the suspension needs to restore its original position to be ready for the next challenge. To do this the suspension is equipped with a spring, which changes its length according to the vehicles load distribution. A high weight load makes the spring shorter and moves the suspension in one direction. A light load does the opposite.

By using the Equation (2.1), Hooke's Law, it is possible do determine spring compression or elongation by the applied force. This means that the spring compression or elongation is proportional with the applied force.

$$F = -kX \tag{2.1}$$

Where:

F = Force applied on spring

k = Spring constant

X = Elongation or compression

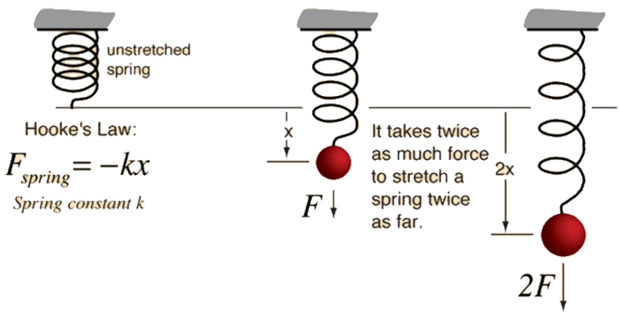


Figure 2-7. An illustration of Hooke's law where two times the force, causes two times the displacement [20].

Typical automotive spring types include compression springs and leaf springs, but other types are also used. It is also important to mention that springs don`t absorb any movements by itself, and needs to be equipped together with a damper to gain system shock absorption.

Figure 2-8. Leaf springs have been used since the 1800s, while helical compression springs is the most used in the automotive industry today [21] [22].

2.3.2. Dampers

While springs are being used to provide a proper weight distribution and keeping the wheels on the ground for uneven surfaces, the dampers mission is to absorb kinetic energy. Kinetic energy is energy caused by motion [23], and is defined by equation (2.2). This formula tells us that kinetic energy grows exponentially by the increase of velocity.

$$K = \frac{1}{2} mv^2 \tag{2.2}$$

Where:

K = Kinetic energy

m = Mass

v = Velocity

A damper transforms the kinetic energy into another form of energy, heat, and the equation explains us how the importance of a damper grows by the increase of vehicle speeds. In our case with the Thorvald robots, the speeds are as low as 3,5-5 km/h, which not necessary gives us the need of dampers. The vehicle could probably be just fine without dampers. Unfortunately, the robot could be equipped with sensitive sensors that are vulnerable against vibrations or other fluctuations. So while a damper could seem unnecessary, it might be enough to avoid the worst movements caused by the tires or surface or other factors.

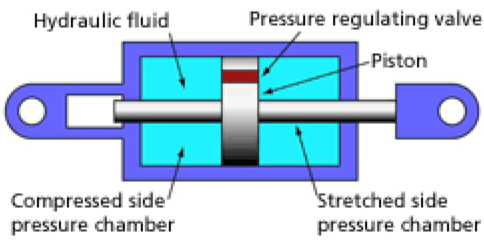


Figure 2-9. How a damper compresses the piston and forcing the oil to flow from the compressed chamber to the other chamber via the piston valve. This way, the damper can transform kinetic energy into heating up the oil because of the oils high viscous properties [24].

2.3.3. Combined Spring and Damper systems

An automotive suspension consists of the combination of a spring and a damper, which is either separately mounted or combined. There are also types of shock struts that have the function of both springs and dampers by combining the viscous properties of oil together with the cushioning properties of air or a gas. These were first developed for the use on aircrafts for lightweight purposes known as the oleo strut, but similar principles are now also commonly used on bicycles and other vehicles.

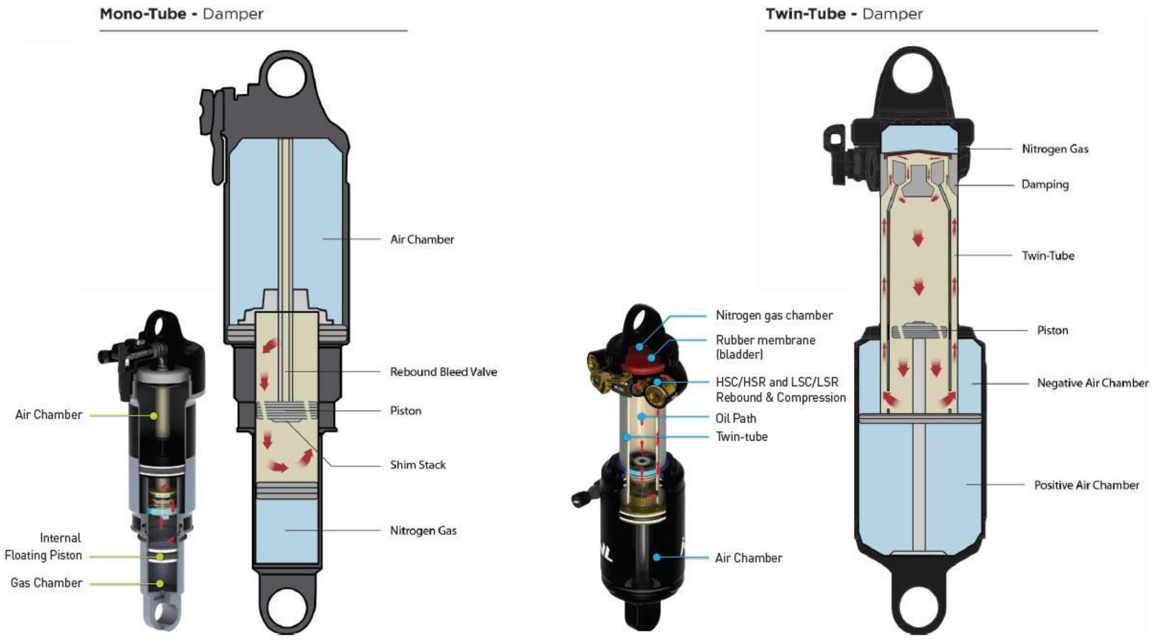


Figure 2-10. How the oil strut is combined with air or gas chambers to create damped and springing movements [25].

2.3.4. Suspension Links

The part of the suspension systems that separates the motions between the wheel assembly and the chassis is called the suspension beams or wishbones as in Figure 2-11. These heavy-duty links make it possible to capture and transfer kinetic energy from the wheels to the dampers.

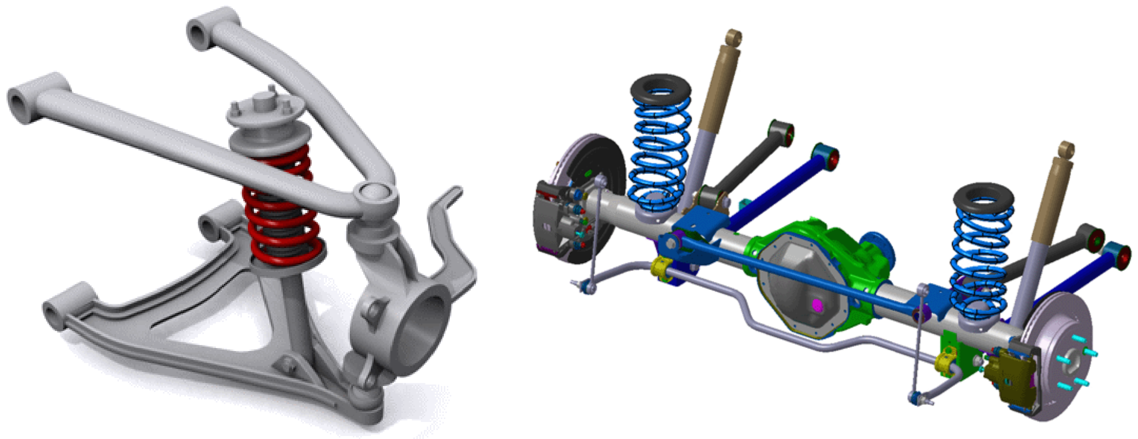


Figure 2-11. To the left, double wishbone suspension. To the right, a pivoting rear axle suspension [26] [27].

The typical wishbone is in either A- shape or H-shape, where the A-shape is use for rotating wheels, H-Shapes usually used on the rear non-rotating wheels. In Figure 2-12 you can see different types of vehicle suspension configurations.

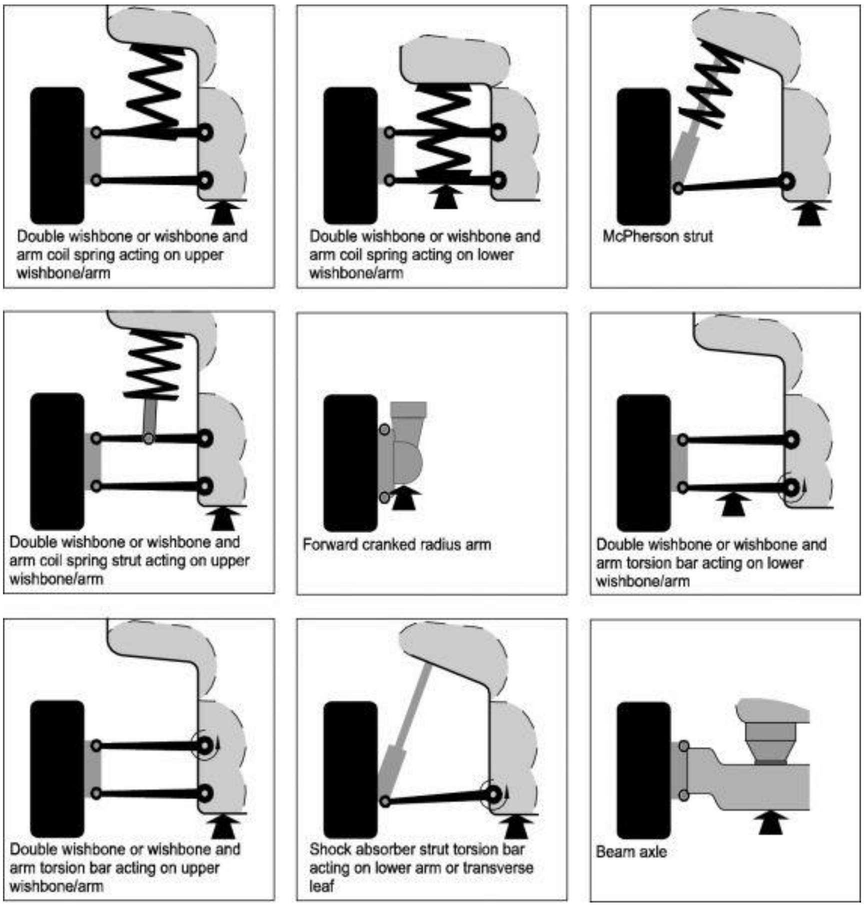


Figure 2-12. Different types of suspension configurations on vehicles [28].

Specially designed automotive suspensions for automotive cars have often suspension arms with slightly different lengths for angular compensations of the wheel when a car is banking in a corner [29]. These adjustments are merely for increasing high speed handling performance. The robotic platform is designed for much lower speeds at about 3,5 km/h, so parallel wheel movement with suspension arms of equivalent lengths is both wanted and accepted. The robotic operating system is pre-programmed with accurate wheel bases and wheel distances to be able to calculate every movement based on the control inputs.

2.4. Vehicle Height Adjustments

Vehicle height adjustment is not only for gimmick "bouncing car" show off purposes. These systems are developed to adjust and level the ride height according to the load of the car or truck and to maintain vehicle driving performance and safety. Some sports cars even have active suspension that continuously and individually customize the ride height of each wheel to the surface, and even how soft or hard the damper-spring system works.

This way it is possible to drive over rough roads without even noticing, depending on how fast the system reacts.

On the Thorvald platform, one thought is to increase and decrease ride height for automatically picking up tools and transport it without touching the ground. I'm looking for what kinds of systems that can achieve this function, which are discussed further.

2.4.1. Manually actuated

There are spring-damper systems that allows you to adjust ride height by either turning a retaining nut that adjusts the helical spring position, or changing anchor point positions. In an air-, or gas-cushioned shock strut it is possible to increase air pressure to achieve ride height adjustments. A compressor or hand pumps for bicycle type shock absorbers could achieve this.

2.4.2. Hydraulically Actuated

To provide excavators their required heavy lifting or digging work, it is usually equipped with hydraulic actuators. These systems require an oil reservoir, pump, pressure regulation and hydraulic valves and solenoids to regulate. It is a powerful system, but it is known to cause leaks and is a relatively heavy system compared to other systems. The main advantages are that hydraulics oil does almost not compress, causing it not to spring or absorb energy. This makes it capable of moving much higher loads than other mediums.

2.4.3. Pneumatically Actuated

Other ride height adjusting techniques include the use of compressed air. These systems are often similar to hydraulic systems, but its medium is more lightweight and does not make a mess when spilled. It also does not need a line for fluid return, as the pump is surrounded by its medium. Since air is compressible, it absorbs excessive force causing the systems to last longer, be more reliable, due to less system shock damage. Pneumatic systems are built very simple as it has few components, as well as being very safe. A pneumatic prototype can easily be built together with a programmable microcontroller like in Figure 2-13.

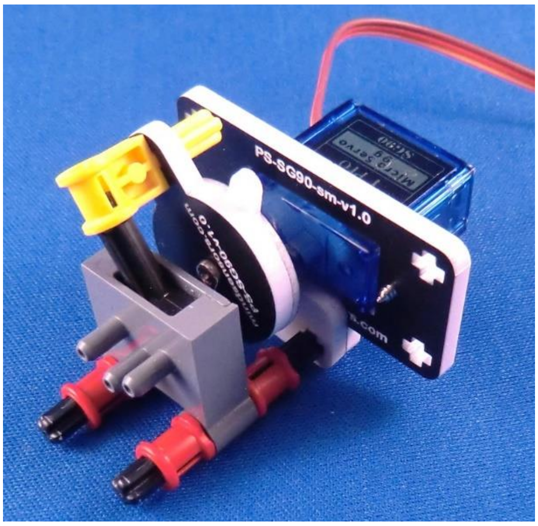


Figure 2-13. An example of how a pneumatic prototype could be built by using Lego® Pneumatics. In the picture the electric servo controls a pneumatic valve that is connected to an Arduino microcontroller [30].

3. Materials

3.1. Material Properties

There are a number of ways to describe a material other than a molecular perspective. Different kinds of materials may be combined into making a material with entirely different characteristics than the materials by itself. Some materials can even be heat treated to achieve desired properties. As a result, there is an enormous amount of material types to choose from, and you should be able to choose the right one for a project. Following are properties that are widely used to describe a material.

Young's Modulus

The Young's modulus, also called E-modulus, is a term that is used to describe the materials linear elasticity. This means that a low value is extremely flexible, like rubber. High value materials are often called brittle, like glass for instance. A flexible material can endure a much higher elongation without breaking, than a brittle material. While a more brittle material is better to withstand movements. To find a materials elastic property, a cylindrical test piece is undergoing tensile testing in a machine that tries to pull the piece apart. The calculation of the elongation ε is then based on the difference in length divided on the original length. Tensile strength is the force applied to the material divided on the area of the test piece.

Poisson's Number

As a material stretches or compresses the cross-sectional area will either decrease or increase. Poisson's number is the relationship between the materials elongation and cross-sectional area, and is usually around 0.3 for aluminum and steel.

Shear Modulus

The shear modulus is the ability to resist shear forces for a material, and is calculated as the relationship between the Young's modulus and Poisson's number.

Yield Stress

As a material is deformed by stretching there is a limit where the object can return to its original length, and is called the elastic yield stress limit. If the material is pulled further, the material gets permanently deformed, but will not break. Yield stress is measured by dividing the pull force with the cross-sectional area, so the SI unit is in N/mm^2 or MPa.

Tensile Strength

The absolute maximum stress a material can withstand before breaking is the tensile strength. This is usually somewhat larger the yield stress, depending of the properties of the material. Tensile strength is measured in N/mm^2 or MPa.

Von Mises

Usually, materials are not only pulled in one direction. It is often a combination of axial forces, radial forces and moments. A way of calculating such forces is to use the Von Mises hypothesis which is an estimate of the combined forces in a material.

3.2. Material overview

Often metals are categorized as ferrous and non-ferrous materials. Ferrous metals contain iron, or ferrite and is typically known as steel alloys or metallic irons. This is a versatile material which is economical to extract compared to other metals. The disadvantage is that ferrous metals are subject to corrosion without any treatment, its high density and its ability to conduct electricity.

Non-ferrous metals do not contain any ferrites and are known as metals like aluminum, magnesium, copper and titanium and more. These are used as base metals for alloys including nickel, zinc and zirconium. The non-ferrous metals are divided into wrought and cast alloys. Low ductile, or brittle, and non-formable alloys are used as cast metals, while the formable are called wrought alloys. Alloys are also divided into het treatable and non-het treatable alloys.

Materials are more than metals and other typical structural materials to consider are plastics and composites. Plastics are not necessary weaker materials when compared to weight. A common way of describing material strength is the Specific Strength, which is calculated as the Tensile Strength to Specific weight – ratio shown as Formula (3.3). This is important for designing lightweight systems that need high efficiency, such as vehicle design where energy consumption is a priority.

$$\text{Specific Strenght} = \frac{\text{Tensile Strength}}{\text{Specific Weight}} \tag{3.3}$$

The world is seeing a huge gain in popularity of 3D-printers, caused by the low costs, making it available for everyone. These printers can print complex plastic parts with an internal honeycomb-structure, making it unbelievably lightweight and strong. This makes plastic a worthy candidate as a material. In Figure 3-1, there is a comparison between different materials specific strengths and their specific elasticity.

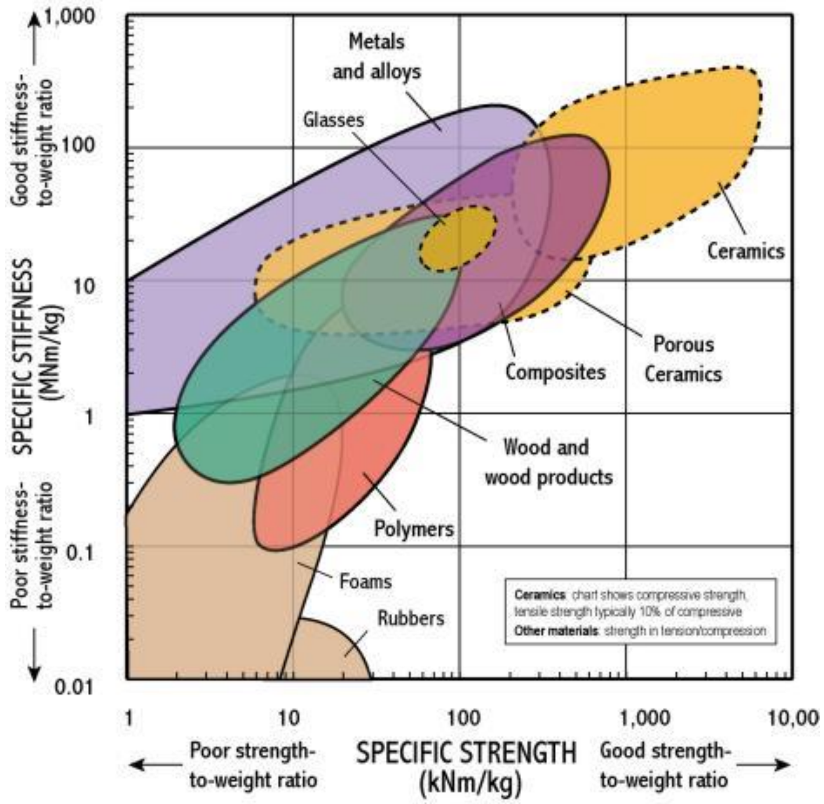


Figure 3-1. A diagram showing material properties. Specific strength on the X-axis and the Specific stiffness on the Y-axis [31].

3.2.1. Steel

Materials in agriculture, especially farming tools are exposed to abrasion, moments and deformation when put into the ground trailing behind the tractor, so materials need to endure such violations. Steel is commonly used for agriculture for this reason among being weld-able an easy to fix for most farmers. Steel comes in a variety of qualities and has a Young's modulus of about 210 000 MPa [32], tensile strength between 250 MPa and 1000 MPa. The costs and characteristics of steel makes it suitable for powerful machines made for farming purposes. Steel is an alloy which is a mix between the main substance iron (F) and just below 2% Carbon (C) for most steel alloys. By changing the amount of carbon, it is possible to change the characteristics of the steel. Low values of carbon make the steel easy to weld and makes the steel more ductile. Higher values of carbon increases abrasion resistance, tensile strength, hardness, and improve the reaction to hardening.

Hardening of steel causes iron and carbon to form different types of structures, with different heat treatments that bind the molecules together. The stable form of steel is the ferrite structure. When the steel is heated to a certain level it turns into an austenite structure. This allows the carbon molecules to get evenly distributed in the spaces of the structure. If the steel is slowly cooled, the structure turns into ferrite again, unless is gets rapidly cooled down. This causes the structure to be locked in an austenite structure, causing stiff and strong properties.

Steel is a common structural materia, which is available as many alloys, and corrosive resistant variations. Steel does have high strength to weight ratio, which means lower efficiency for dynamic systems where weight is critical.

3.2.2. Aluminum

Aluminum is characterized as a lightweight material with a density of 2.7 g/cm^3, compared to steel with a density of 7,9 g/cm^3, but certain alloys has a larger specific strength than steel. It has also good corrosion resistance in its pure form, but is reduced as an alloy. Typical alloy compositions are copper, manganese, magnesium and silicon. Aluminum has also good electrical and thermal conductivities, which makes it suitable for use with computers and other heat generating components.

Pure aluminum has relatively poor mechanical properties except for high ductility, so for structural appliances it is necessary with hardened aluminum alloys. Different aluminum alloys have different properties, such as being weldable, formable and even seawater resistant. Aluminum alloys are categorized as wrought, nonheat-treatable alloys, wrought heat treatable alloys and cast alloys. These categories are identified by the use of a four-digit number such as the pure 1000-series approved for food handling and the 2000-series for use on aircraft structures. Table 3-1 has a selection of a few common aluminum compositions and heat treatments. This table illustrates how material strengths increases with material compositions and heat treatment.

Table 3-1. Mechanical properties and compositions for a few common aluminum alloys. Courtesy of Callister and Rethwisch [33].

Aluminum Association No.	*Composition (wt%)[a]*	*Condition (Temper Designation)*	*Tensile Strength [MPa]*	*Yield Strength [MPa]*	*Ductility [%EL in 50mm]*
1100	0.12 Cu	Annealed (O)	90	35	35-45
3003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110	40	30-40
5052	2.5 Mg, 0.25 Cr	Strain Hardened (H32)	230	195	12-18
2024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat-Treated (T4)	470	325	20
6061	1.0Mg, 0.6 Si, 0.3 Cu, 0.2 Cr	Heat-Treated (T4)	240	145	22-25
7075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23Cr	Heat-Treated (T6)	570	5005	11

Hardening of aluminum is typically classified with a capital letter followed by a number or two. The most common hardening classifications are the O, T3 or T6, where O is soft and easy workable, typically “as fabricated”. The T3 means that the alloys are solution heat-treated and naturally age hardened. T6 is similar to T3, but with an artificial ageing.

3.2.3. Polymers

Both plastics- and rubber family are common materials categorized as a polymer. A range of polymers are organic, and are based on carbon, hydrogen or other non-metallic elements [33]. It usually consists of a large or long chainlike molecular structure. Common polymers include nylon, polystyrene, polyethylene, poly vinyl chloride, silicone rubber and many more. Low densities and great ductility characterize it. Even if polymers are not as strong or stiff as metals, the specific strength ratio is comparable to metals. The drawbacks include getting soft with relatively moderate temperatures and getting brittle at low temperatures. In an outdoor environment some polymers are sensitive to UV-radiation and ozone, which causes polymers slowly deteriorating with time.

As mentioned earlier, plastics are used as a 3D printer medium, especially Acrylonitrile Butadiene Styrene (ABS) and Polyactic Acid PLA. These production methods can contribute into increasing the specific strengths of plastic.

3.2.4. Composite

From the word compose, which means a composition of at least two different materials, we get the composite [33]. A composite allows us to combine the properties of at least two different materials in the way we desire. Although composites are known for fiber materials, it could also mean a combination of metals, polymers and ceramics. Fiberglass is a relatively strong, flexible and lightweight material. It is usually combined with an epoxy, which is a resin cured by a hardener, or a polyester. Other composites include the use of carbon fiber reinforced polymer, which is even stiffer, stronger and more flexible than glass fiber. For other special uses, is the aramid fiber, commonly known by the trademark, Kevlar®.

4. Production Methods

4.1. Plastics Production Methods

Production methods differ relative to the choice of materials as different material often demands different manufacture methods. The choice of materials often land on what kind of production method used, which sums down to the scale of production.

In this section I will consider common production methods and materials that are applicable for different demands and scale of the electronic compartment.

Injection Molding

One of the most common plastic production methods today according to ENSO plastics [34], is the injection and extrusion molding. This method is using granular plastic polymer compressed into a nozzle, which injects the polymer into a pre-fabricated mold [35]. The plastic piece is rapidly cooled down and separated from the mold. The profitable production batch size is between 10.000 and 1.000.000 which is not applicable to a prototype. Other limitations involve a limited product weight of 1,5 kg according to the manufacturer Biobe AS [36].

Rotational Molding

This production method is used to create a fully closed non-complex voluminous product [35]. Rotational molding involves a mold that is heated while containing polymer powder. The mold is continuously rotated while heating and cooling and is separated from the mold.

Compression Molding

By pressing two dies together with a plastics charge in between, we can create a low to medium complex plastic product. This involves the cost of making a die, so that the economic batch size is between 5.000 and million products.

Resin Transfer Molding

Resin is a chemical, highly viscous polymer mixed with a hardener that cures after time and creates a hard plastic product [35]. This polymer product can be feed into a mold before curing and create a medium to highly complex product when set. The need of a die will cause high costs for a few required products.

3D printing

By equipping a computer numerical controlled 3-axis machine with a plastic ejector nozzle you get a 3D-printer. This way it is possible to make complex shapes that would be hard to make otherwise. These machines can print internal lightweight structures to increase the specific strength. Recently “Eik Ideverksted”, an interdisciplinary workshop for student and others have acquired a composite 3D printer. This machine prints every other layer of nylon and glass-, carbon- or Kevlar® fiber. Some unofficial testing claims a ten-ton weight to brake a 3D-printed link as shown in Figure 4-1.

Figure 4-1. Using a composite 3D printer, a blog claims that this printed chain link required a 10 tonn weight to break.

4.2. Composite Production Methods

Open Molding
According to Composite World [37], a low cost and common process of making a composite product is the open molding process. This involves the use of a one sided composite mold that is used repeatedly, and is manufactured first, by making a positive plug, often made out of wood. This plug is treated and painted with gel coat, often used on boats, that makes a surface that easily slips. A negative mold is then created by covering the plug in a composite material, the low friction gel coat will cause the plug to easily be removed after curing. The one-sided mold is then ready for mass production. The advantage of this method is that a mold can be created without heavy machinery and is easy and relatively cheap to produce. This production method is suitable for a few products but grows more economical with quantity.

4.3. Metal Production Methods

A lightweight production method for metals is necessary to keep the robot within the weight limit listed in the demands. Because of the heavy nature of metals compared with plastics [33], production methods listed will be limited to processes using sheet metal.

Press Forming
Deep drawing is a press forming method used to form metal containers such as a boiler, kitchen sinks and metal boxes. By the use of a high-pressure punch and a die, the method can produce simple shaped containers or forms. The process demands fabrication of expensive dies, or molds that is suitable only for a large quantity of products [38]. Bending is another press forming method, using a metal sheet bending bench, or automated systems. Common materials for bending is steel, brass or aluminum [39].

Depending on which material is used, different bend radiuses are allowed. This is important to follow for preventing the material to crack. It is hard to bend a complete box. To do so it needs to be put together by multiple sides and parts.

Figure 4-2. This image shows a deep drawn metal container, and a sheet metal enclosure produced by bending. [38] [40].

4.4. Plasma Cutting

Plasma is a state of matter and is created by heating up ionized gas. By channeling the gas into a high pressure jet, it is possible to cut through any kind of conductive materials. When this cutting technology is mounted on to a CNC-machine it's possible to cut advanced figures and forms out of metals sheets up to about 20 mm thickness. This is a quick and easy method. The downsides are not so clean cuts, and gets worse with the thickness of the material. For most applications this is more than enough.

4.5. Water Cutting

Water cutting involves cutting metals with a high pressure water jet. It seems unbelievable that the soft and essential fluid is capable of cutting such hard materials, but we can see this in nature as rivers cuts through canyons and valleys during thousands of years. Water cutting machines have the same process but of course speeded up a lot. By equipping this to a CNC- machine it is possible to cut this out any kinds of figures with a precise clean cut.

4.6. Material Joining and Modular Connections

The perfect example of a modular connection is the Lego®. These tiny pieces of plastic can be put together in infinite ways to create the desired form, and remains a huge inspiration since childhood. The older the kids, the more advanced series of Lego®-pieces can be bought, and today even grownups can be building advanced robots using the programmable Mindstorms-series.

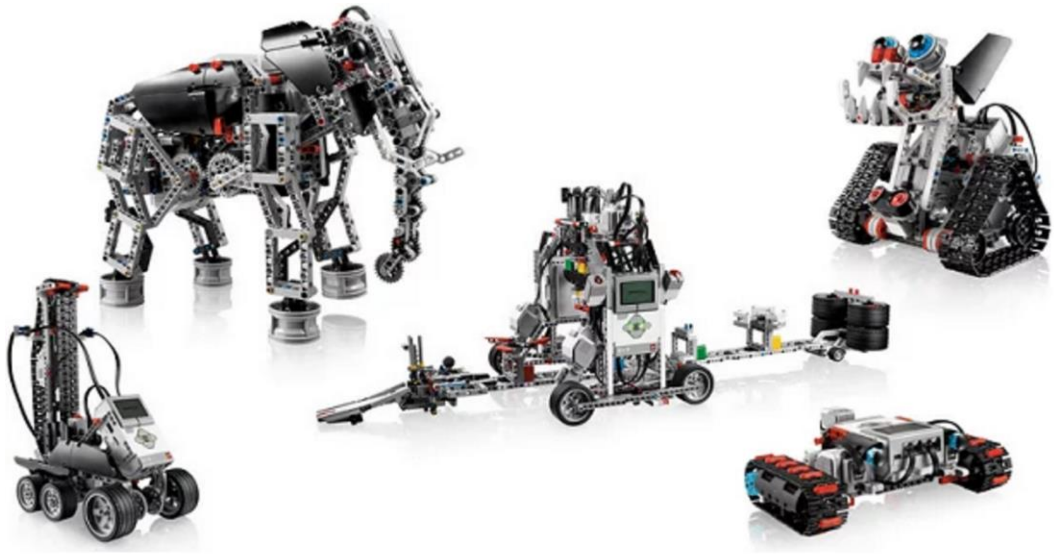


Figure 4-3. The Lego® Mindstorms series, used by kids and grownups as a gateway to learn basic robotics [41].

4.6.1. Welding

Regardless of how metal sheets are manufactured, it sometimes needs to be joined together to form the desired product. One method of joining metals is by welding [33]. This method uses an open-loop electrical circuit with nodes between the workpiece and the electrode. When the electrode touches the workpiece, it creates a close-loop circuit, which creates high flow of current in between. This causes high enough temperatures to melt the material. A filler rod is gently supplied to fill in the need for material in the weld pool.

This is a rapid way of joining metal elements, but welding of sheet metal demands highly trained welders because the high local temperatures, and low moment of area of a thin sheet causes the metal to curl [42].

Welding of aluminum alloy is not known for being a strong and lasting joining method for structural elements. Cold worked aluminum alloys will according to Lincoln Electric [43] get soft or annealed in the local areas where the weld is inflicted. Heat treated aluminum gets poor mechanical properties when welded, as the welds surrounding material get heated well beyond heat treating levels. For these reasons aluminum will lose about 30-40% of its parent material strength. This does not mean that aluminum is not weld-able, but it is not recommended for dynamic appliances, unless welded by someone with the right competence and with the right alloy. I should also be properly dimensioned for the desires strengths.

4.6.2. Riveting

Riveting is the joining method that is most used on for example aircrafts structures in according to the Jeppesen Standard Aviation Maintenance Handbook [44]. These structures are continuously in motion during flight by both turbulence and alternating cabin pressure. Rivets proves to be an efficient, reliable and safe way to join aluminum together, compared with welding. When riveting, the rivet stem expands and creates an airtight solid connection that will not budge or create movement between the aluminum parts.

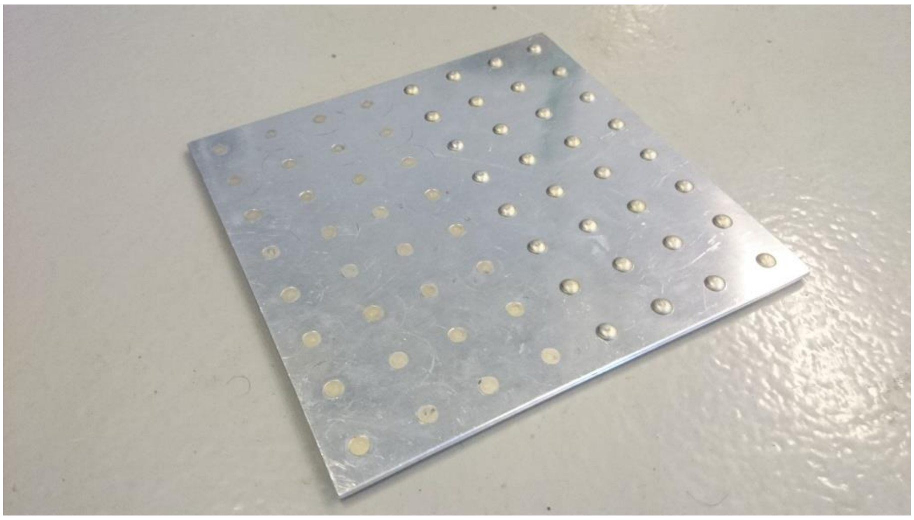


Figure 4-4. This is a riveting sample from my time as an apprentice in the Scandinavian Airline Services, showing both cupped and countersunk rivet heads.

4.6.3. Bolted Connections

Bolted joins material together by three principles. One is shear connections, one is tension connections and the last is friction connections. Tension bolt connections are probably the most known bolt connection we know of. A member is simply bolted down to a surface and the bolts bear an axial force. Shear bolt connections are often used with a close fit bolting hole, with the minimum allowance of movements. In these cases, it is the bolt that bears the most of the stresses in form of transverse radial forces. Friction connections can have loose fit bolting holes, and the connection relies on friction between the member and the surface. These connections can bear both axial and radial forces depending on the bolt pre-tension.

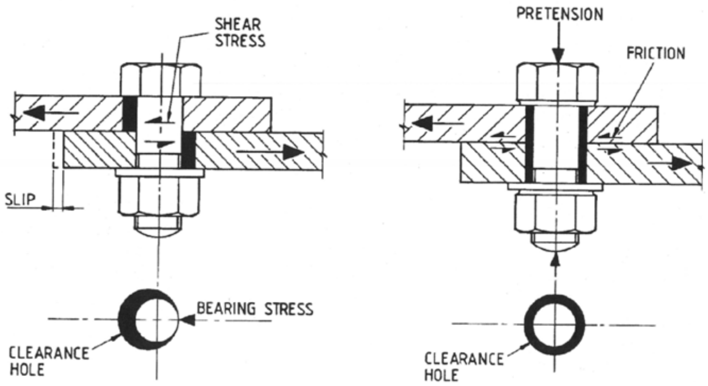


Figure 4-5. Examples of shear bolt connection and friction connection [45].

4.6.4. Modular Connections

An essential piece of knowledge to gather when making a modular system is the modular products available on the market. There is a lot of modular concept designed for the process industry using everything from food packing systems to parcel sorting businesses. These typical routine missions are often individually designed for each individual market or workshop. Known manufacturers of these modular concepts are Rose+Krieger, Aluflex, Item and so on. Product are catalogue based and hours can be spent to find suitable combinations of their products. It ranges from aluminum profiles and stainless steel items and cart wheels.

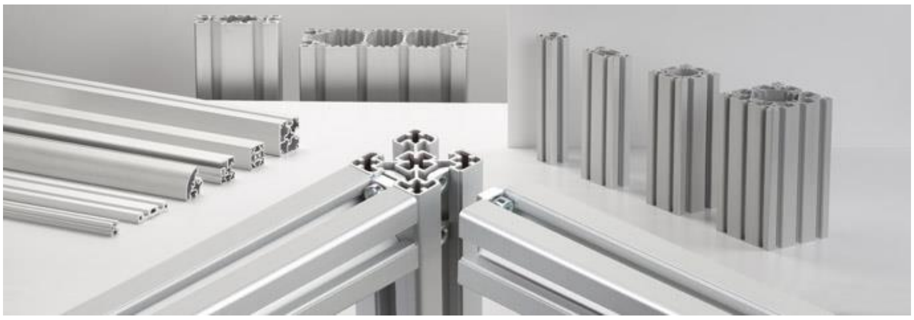


Figure 4-6. Modular aluminum concepts from Rose Krieger [46].

Modular connections can also be made and especially designed for the right purpose. Examples include bolted flange connections between modules, tube clamps and specially formed friction fittings. Figure 4-7 shows an example of the previous modularization of Thorvald I, compared with a clamp type fitting that can annul the movements between the elements with the right bolt pre-tension.

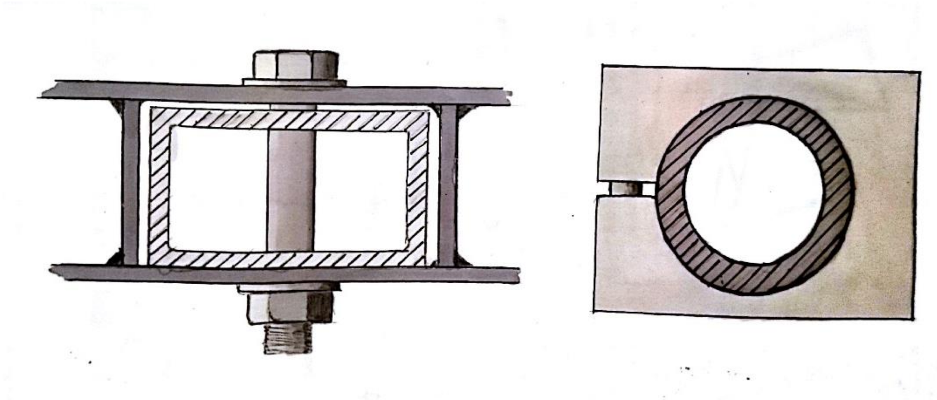


Figure 4-7. To the left, the modular system of Thorvald I, using rectangular fittings, and how movements can be annulled by using round clamping fittings, creating an even and close fit. The gap distances in the left illustration are exaggerated.

5. Process of Design and Calculations

As modularity is one of the prime objectives, I have mainly been researching modular systems and patents. I have also used a lot of time drawing and finding my own modular concepts. The development and ideas has gradually and continuously improved during the master thesis period.

5.1. Requirements

Vehicle Requirements

- Safety comes always first (HSE/HMS)
- Highly modular
- Lightweight
- Outdoor muddy, watery environments
- Four-wheel drive capabilities
- 360° Four-wheel steering capabilities
- Rigid frame
- Easy tool change
- Minimize maintenance
- Adequate wheel weigh distribution on uneven surfaces
- Satisfy increased degree of Technology Readiness Level (TRL) compared to previous model

Table 5-1. Design limitations and requirements.

Design limitations	***Limits***	
Length * Width * Height	1200 * 1650 * Unlimited [mm]	
Weight	200 kg, 200 kg payload	400 kg
Wheel base	~1500 mm	Adjustable according to costumer demands
Component footprint	Max. 300 mm width	
Propulsion	500 W per wheel module	

One important key feature that often overlooked is the safety issue. A robot may hold many dangerous aspects that need proper consideration, such as batteries that contain enormous amounts of energy. A short circuit in the electrical system can cause a fire that is hard to stop, even for fire rescuers, and often end in burning to the ground. Electric systems also increase the risk of electric shock. Other safety issues lie in the fact that this is a moving robot which contain many moving parts, and can cause collisions between objects and human beings. The right safety precautions need careful considerations.

One of the demands for the agricultural project is that the robot is to be broken down into simply changeable modules to make the robot meet the most likely demands required by different farmers with different needs. This means that every main component needs flexible solutions to maintain the overall modularity of the system. The electrical container is not an exception and needs proper demands in both design and development.

Soil compaction as previously discussed is one of the main factors of building the robot in the first place. By designing the robot lightweight enough, the thought is that the fuel consuming ploughing of the fields could be avoided or at least reduced needs. Other benefits include less emission of nitrous oxide caused by anaerobe conditions in the soil.

Field conditions may include rain, moist, and dirty everyday conditions in northern Europe, while other parts of the world have even extremely hot conditions. These more or less normal conditions need consideration while designing a robot. Components need to have the right temperature range, and water sensitive components need proper water protection.

Suspension and frame design needs to be adapted to the four-wheel drive and four-wheel steering system equivalent to the previous model of Thorvald.

The robot needs to be able to have interchangeable tools, and the flexible frame of the first Thorvald version proved it a challenge for future autonomous tool changes. It became clear that the requirements of the next version of the agricultural robot would be a rigid frame. This means, that to keep the wheels on the ground at any time, the platform needs a form of suspension.

By equipping the platform with components that satisfy and withstand the environmental conditions, and its designed parts properly dimensioned, it is possible to give the robot a long lasting life with the minimum required maintenance work. Even though, for properly dimensioned parts, as long as it contains movable parts, there will always be need for maintenance, and a maintenance procedure needs to be described.

Since this is a second prototype, in its last form, I will have to prove that the robot is closer to the end goal of Technology Readiness Level (TRL), than the last version in the areas that needs improvement. One of the drawbacks with the last version was the modular rectangular tube connections that were not rigid enough, and created movements caused by the gaps between the outer tube and the inner tube.

5.2. Frame Design

5.2.1. Early development of Modular Design

The beginning of the project was presented with the concepts of two individual robots. One was to supersede the Thorvald I with improvements, and the other was presented as the Thora robot, which is tall enough to drive in the field tracks without touching the full-grown grain. The Thora robot was supposed to be simpler in design and have fewer components and two-wheel drive to make it cheaper, it would also be equipped with a weed spraying system. Figure 5-1 shows an example of early ideas for design, with an inner structure covered by an outer shell. This version would have similar frame flexibility as the first prototype. The modularity involves the separate propulsion frame, battery and electronics box, and rear caster wheel.

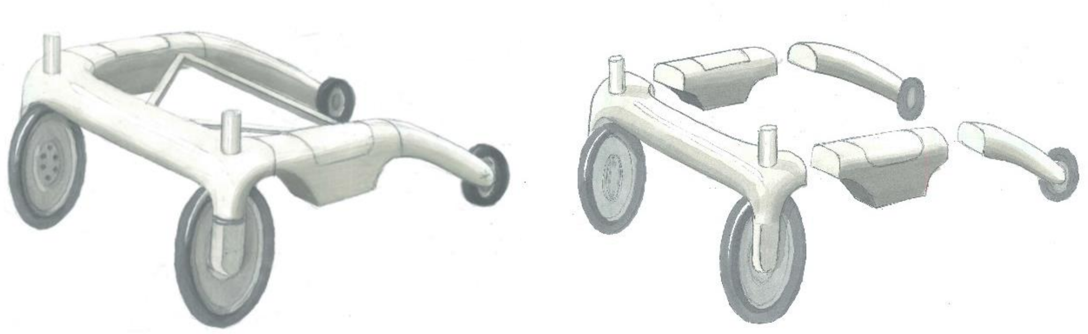


Figure 5-1. This is an illustration of one of the early ideas as part of the unofficial brainstorming process. The idea was an internal frame covered with composite outer shell. One idea was also making a structural shell, similar to a monocoque structure.

Other ideas of suspension is a flexible frame with the torsion bar mounted slightly more backwards on the frame like in Figure 5-2. This way, the front wheels would be able to flex individually which would reduce the roll of the vehicle. Other features of this idea is the modular bolted flange connections that ensures easy, quick change bolting between the main parts.

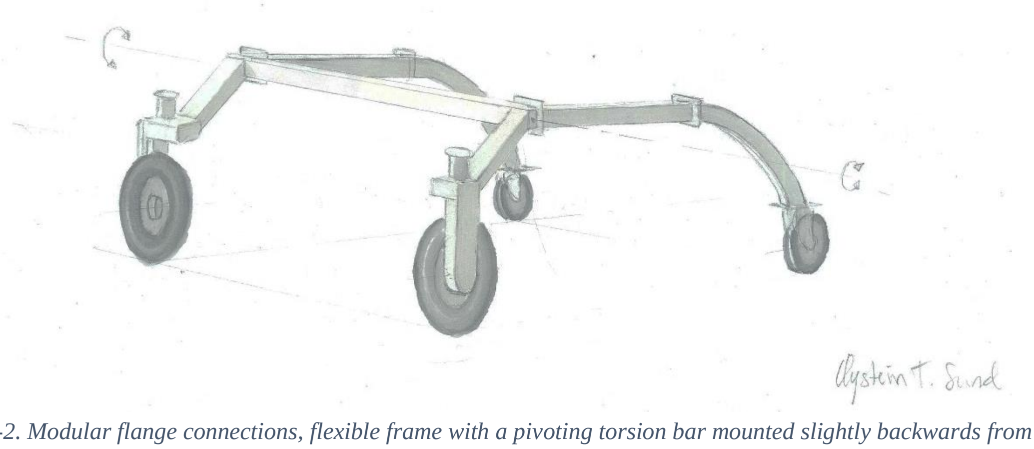


Figure 5-2. Modular flange connections, flexible frame with a pivoting torsion bar mounted slightly backwards from the nose.

A similar concept was made with a composite monocoque design in mind shown in Figure 5-3. Although a sleek, lightweight and streamlined design and use of imagination, it is both expensive to build and could cause modular difficulties and equipment fitting challenges.

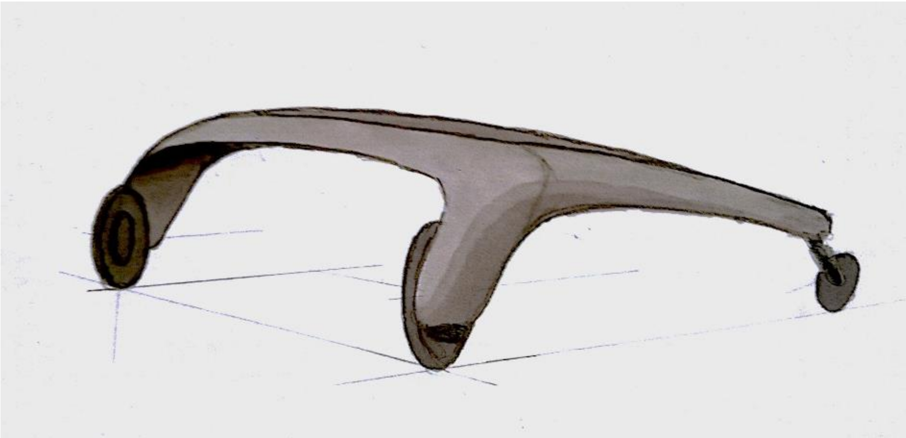


Figure 5-3. A lightweight sleek manta ray design with a composite monocoque structure.

It was discussed in the project-team how a flexible frame made it more difficult for the tool to get an even and well-distributed load, by experience from the seeding tool with Thorvald I, so the idea of a rigid frame was brought up.

The next designs consisted on aluminum profile technology that could be bolted together with barrel nuts in the profile channels. Profile technology could be costly and designs of rigid frames demanded a lot of profile lengths. I also had difficulties with imagining how the suspension could be designed together.

Later, I was trying out the possibilities of making tube frames, these tubes are quite cheap, and generated new challenges in making the frame stiff enough to avoid collapsing the frame by tube torsion. My first designs involved using as much tube modular technology as possible that could be purchased. I quickly realized how expensive this could get. Figure 5-4 shows early ideas of tube design. The challenges in this design was production of the corners, that would require a lot of material and machining hours, if not cut by a water cutter.

Figure 5-4. One of the first ideas of tube connection design and suspension. This required a lot of aluminum material and a lot of machining hours.

After a lot of trials and failures I came up with the idea of designing my own T-connections, the design in Figure 5-5 and Figure 5-6 shows how the T-connections serve three purposes. One is binding the tubes together and the second is to serve as hinge for the suspension, and the third is the possibility of completely removing the suspension and bolt the wheel modules directly to the frame. The purpose of this is to make cheaper platforms for mild surfaces or allow suspension on only the front or back, as it is not always necessary with suspensions all over.

Figure 5-5. Total overview of the nearly final design.

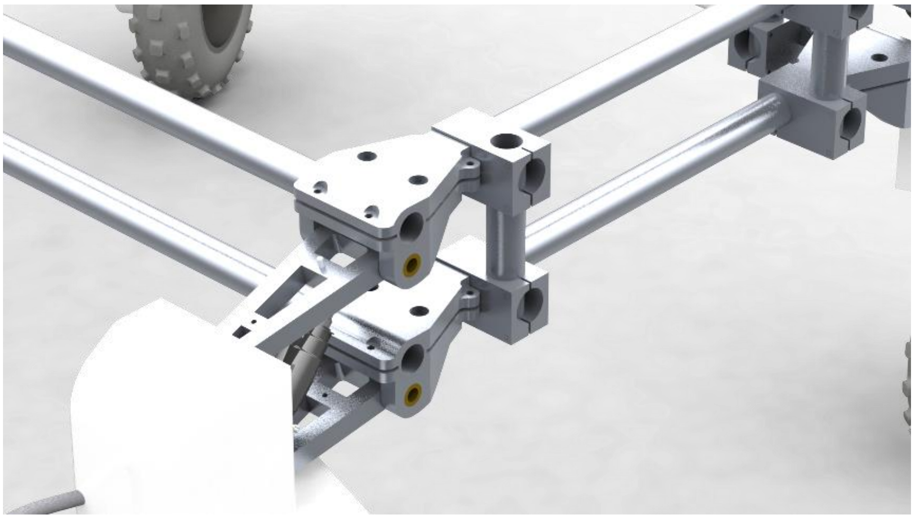


Figure 5-6. Close up picture of the T-connection design and Rose+Krieger aluminum blocks.

This design was still not quite mature yet. I wanted a cheaper solution as the T-connections still demanded a bit of CNC-milling. Also the rigidness of the system would probably not be good enough with the connecting block from Rose+Krieger. When driving sideways these could easily cause the blocks to twist and make the frame collapse.

By further development of the previous design, Figure 5-7, shows the T-connection made easy with plasma cut parts and purchasable aluminum clamps. This is a cheaper and a more lightweight or at least faster way of production for the T-connections, avoiding heavy CNC-milling hours.

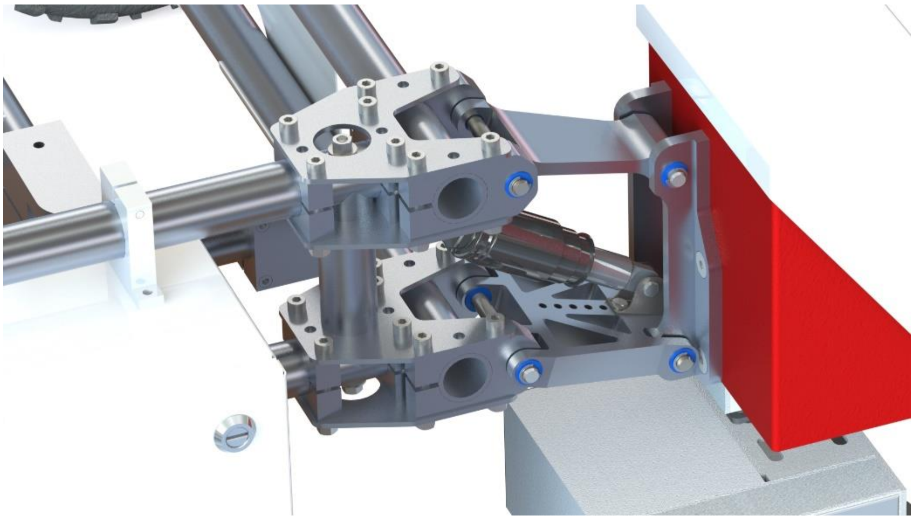


Figure 5-7. Using plasma cut top and bottom plates together with purchasable aluminum clamps, it is possible to create a more lightweight, simple and cheaper T-connection solution.

5.2.2. Choice of Materials

The choice of materials is based on the specific strength of the material, previous design suggestions and costs. This way, making the robot potentially more lightweight. Choices are also based on the way of joining materials and its form of modularity, as friction coefficient between aluminum elements are higher than between steel elements. When arranging a meeting with many of the sharpest minds on the university, and presented our project in aluminum, we got different kinds of feedback. It was mentioned that the robot should be made out of steel to make the robot weld able for the ease of farmers to make own adjustments and equipping. It was also suggested by our aluminum expert, Geir Terjesen, that the robot should be continued with its design out of aluminum as an interesting approach if the goal was to make a lightweight robot. In response, by choosing aluminum material, and the modular design of the system, farmers could do their own adjustment without necessarily having to weld anything. Second, the robot is initially meant as a research platform. That is not available for everyone at this stage.

5.2.3. Special Frame "Thora Module"

One of the criteria for the new version of NMBUs agricultural robot was that it should be able to run over fully-grown grain on the fields. This way the research farmers of Vollebekk could put their own manual anti-weeding spray gear on the attic, and let the robot take care of the same job, eventually. This could promote better health conditions for the sprayers. Since there aren't enough resources for making an extra, specially designed robot, it is natural to take the same robot and build a tall structure that can do the job. As the module needs to ensure 1,5m wheel base and be able to drive over 1,6-1,8m tall grain, the challenge is to get the module stiff enough. Figure 5-8, illustrates a steel truss or space frame design that could ensure a stiff connection.

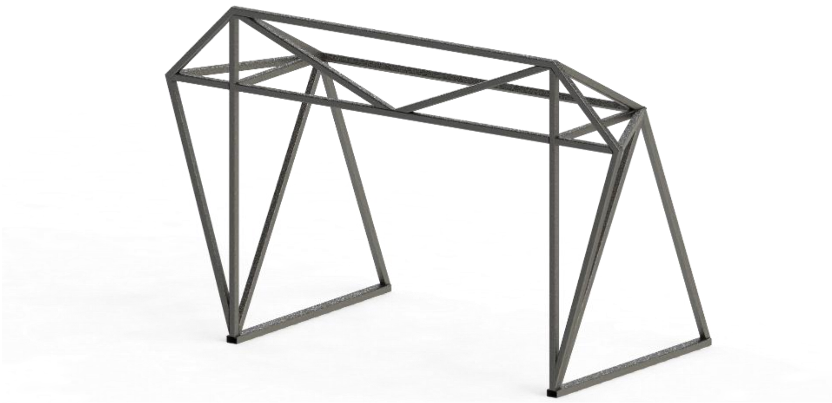


Figure 5-8. Early idea of the Thora module that connects two halves of the robot. This illustration is based on a truss or spaceframe design.

The space frame design does demand a great deal of work like cutting steel tubes and welding. Therefore, I wanted to try a simpler and cheap design. Two single and bended aluminum hoops was one possibility as shown in Figure 5-9 below. This design is however vulnerable against splitting if each nacelle were going separate ways. Aluminum is also hard to weld and is prone to cracks if welded.

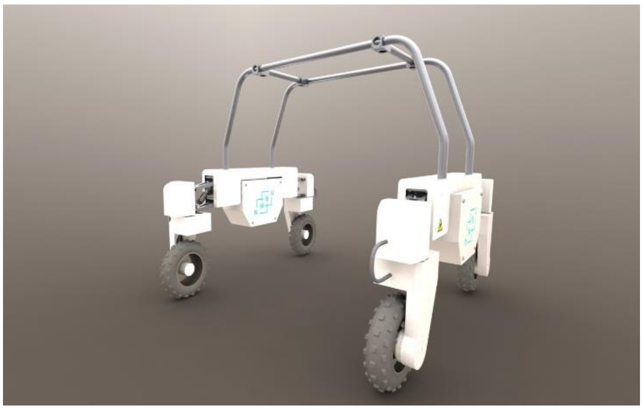


Figure 5-9. Thora extension by using two single tubes bended into a double hoop structure.

One way to make stiffer hoops is to weld on stiffeners in the corners as simulations indicate that the weakest spots are in the bends. Longer parts of the tubes are also sources of displacements, that could be made stiffer by increasing the moment of inertia. If welding of stiffeners where it is needed is the way to go, I should go for a material that is structurally safe to weld. On the same time, the hoops do remind one of a roll cage used in racing- or rally cars. These structures consist of seamless carbon steel, that easily are weldable. Figure 5-10 shows us an example of a typical roll cage, with the main hoop similar to previous design in Figure 5-9.

Figure 5-10. This illustration shows us a typical roll cage for cars, complexity varies with cars. Image Courtesy of

Using the idea of a roll cage, I have found a dealer that sells roll cage hoops and its sizes are more or less exactly, what I was looking for. Using these main hoops for roll cages, I started designing stiffeners and mounting rails for increased stiffness and equipment mounting possibilities. The suggestion is shown in Figure 5-11. Using pre-fabricated roll cage hoops, it is possible to weld together simple elements and the required stiffeners to gain the desired stiffness.

Figure 5-11. Using pre-fabricated roll cage hoops, it is possible to weld together simple elements and the required stiffeners to gain the desired stiffness.

With standard 40 mm clamps it is possible to easily mount the cage on to the Thorvald II tube frame. By the name of the many campus spirits in Ås, Norway, the team wish to name the robot equipped with this module, Thora shown in Figure 5-12 below.

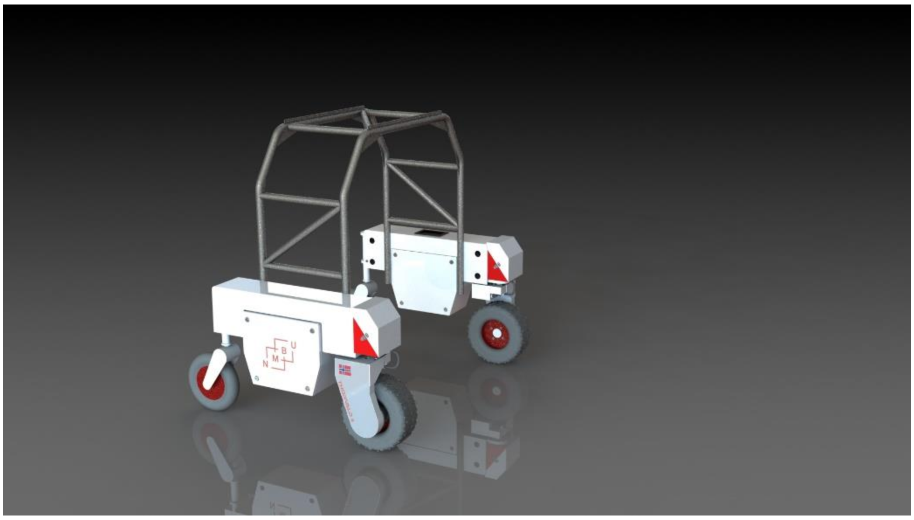


Figure 5-12. The Thora robot equipped with castor wheels and two wheel modules bolted directly to the frame.

5.3. Suspension Design

Suspension for this platform is not only for absorbing the little kinetic energy the robot is generating with its low speed. If the robot ends up with having a rigid frame it is important to allow the suspension to flex instead of the frame. This could result in reduced stress in the frame. There is no necessary need for any damping because of the low velocity of the system, but spring function help keeping an even load on all of the four wheels.

The secondary function of a suspension is the possibility of change in ride heights. Not for demanding terrain, but for the cause of tool change. The idea is to lower the robot, driving into a tool, lift, and lock the tool before driving to the assigned job without damaging the tool underway. When arrived to the assigned piece of land, the robot can lower the tool into the soil for whatever purpose the tool is constructed. When job is done, the robot can return to the station to pick up a different tool. Figure 5-13 shows a series of illustrations on how the robot can pick up tools and transport them safely to the assigned job area.

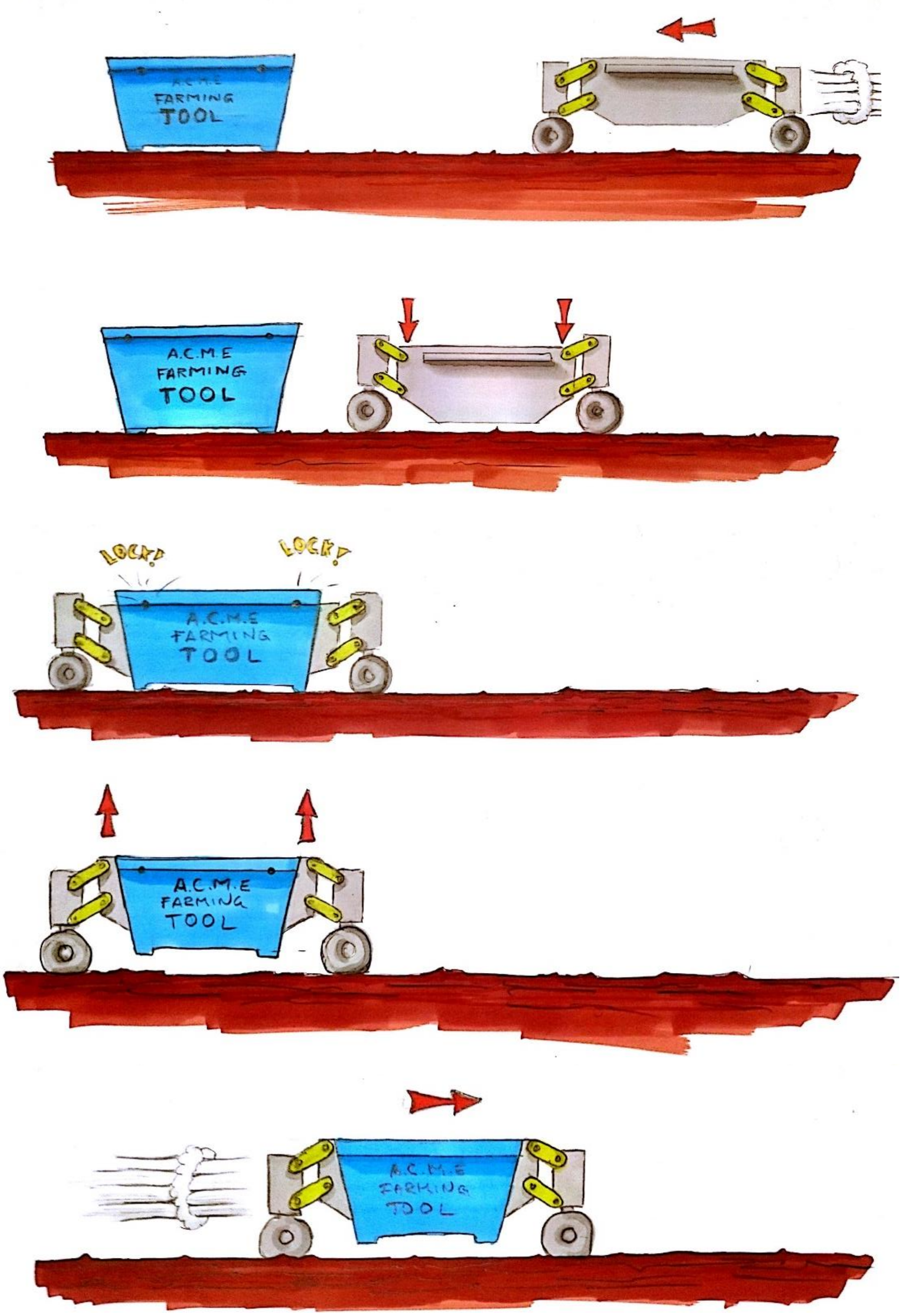


Figure 5-13. Illustration of the suspensions secondary function of picking up tools by rising and lowering the robot.

Interchangeable tools, automatically picked up by the robot could be a challenge. There are many ways to do this, for example using a jacking screw system, leverage system and many others. One more solution is to use the suspension equipped with actuators such as an electric jack, hydraulic cylinders or pneumatic cylinders. An electric jack is probably the simplest system to include in an already electric robot, but is not necessary a very fast system. Another way to actuate a suspension is by using hydraulic pressure, which can be really messy, heavy and complicated. Both principles are stiff systems and do not allow any movement, but combined with springs or shocks electric jack is probably the most likely of the two.

Pneumatic systems use compressed air to actuate movements, and it is a moderately advanced system. The advantages compared to electric jack and hydraulics is that a pressurized gas allows a spring-like compression, acting as a spring itself that allows movements and evenly distributed loads on the ground.

If electrical actuators are preferred, there would be need for an independent shock system to ensure movement of the wheel modules. A way to manage this is to put a shock or spring between the electrical cylinder and the suspension arms as in Figure 5-14. Also instead of a single actuator for each corner as in the figure, one actuator could do the lifting job for two corners at the same time.

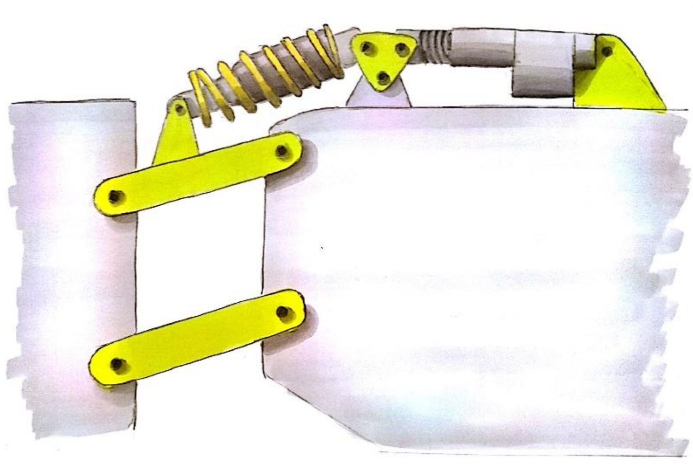


Figure 5-14. If a stiff actuating system is chosen, it is recommended to connect to a spring or damper to allow some movements and even distributed loads.

These high reaching plans are, and will probably be future development plans, as time and resources are not enough for this master thesis. This does not mean that I cannot prepare the suspension for later development.

Further development involves choosing the right set of materials for the suspension arms, what shape and length they should have, based on forces and moments the arms are exposed for.

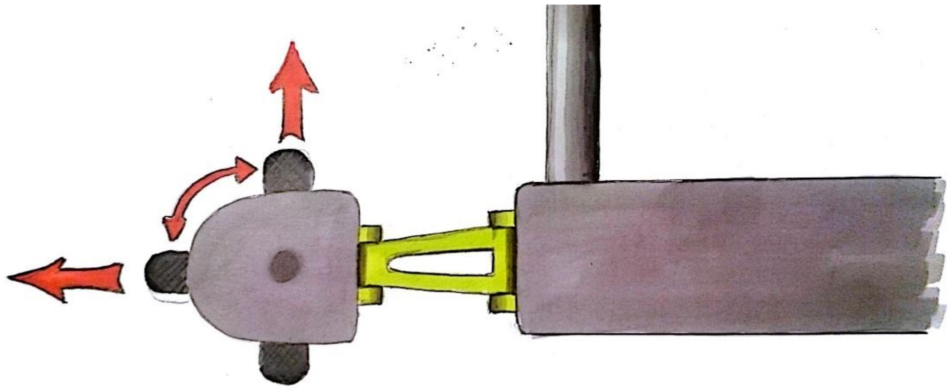


Figure 5-15. This image shows how forces can apply in different directions as the wheel rotate 360 degrees. The force directions shown are the most vurnerlable conditons that needs consideration during design.

5.4. Electronics and Power Compartment Design

The electronic compartment needs to be designed in a way that allow dry operation of vital electrical components. The idea is that, if the outer shell can stop, or partially stop heavy sprays of water, the inner component can reduce their need of water protection dramatically. Highly waterproof components, circuit board conformal coating, or casings are expensive and need to be avoided to create a low budget robotic vehicle.

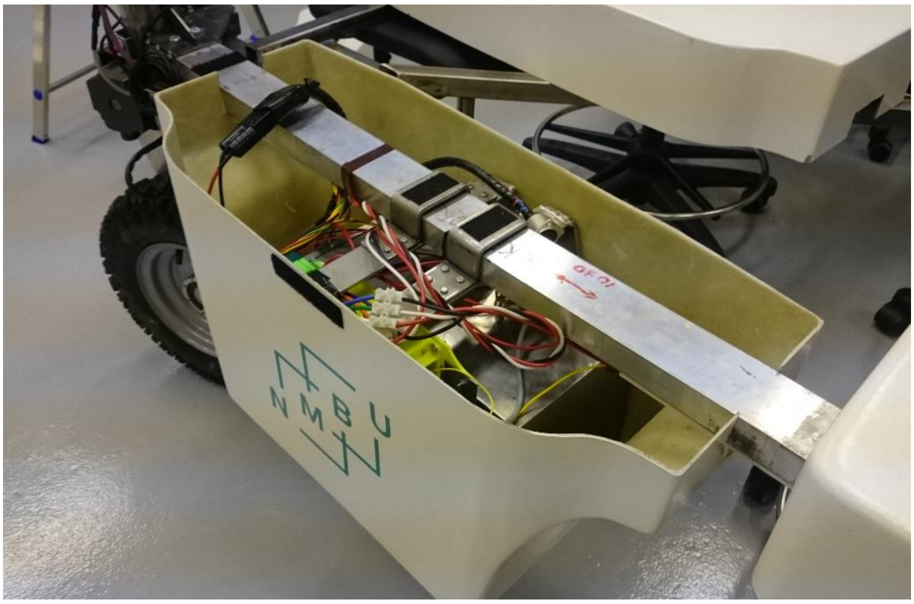


Figure 5-16. The initial electrical compartment of Thorvald I, made out of glass fiber composite. This design only deflected some small amount raindrops.

One of my first ideas included a box made by sheet metal press-form bending of aluminum or steel sheet shown in Figure 5-17. The seal flanges were designed with a double bend to avoid straws of grain to wedge its way into the casing. This double bend can also contribute to deflect high pressure water jets away from the seal. This double flange is better illustrated in Figure 5-18.

Figure 5-17. One of my very first ideas on how the electronic compartment should look like. Two of these halves were to be welded together, and a lid was placed on each side of the box. Note the double flange more closely described in Figure 5-18

Figure 5-18. Double flange can in combination with a rubber seal create a reliable seal by deflecting water jets and avoiding straws of grain being wedged into the seal.

The Electronic component was developed together with the development of the chassis frame design. The first design suggestions of Thorvald II had a rectangular flexible frame, similar to the Thorvald prototype but with bolted flange connections. The parallel development the electronic box also had some ideas as a part of the development, like the one in Figure 5-19 and is latching waterproof flange shown in Figure 5-20.

Figure 5-19. A composite electronic compartment design idea for the early Thorvald II designs.

Figure 5-20. The idea for the composite enclosure involved latches and a compression flange containing a gasket.

Later in the project, me and my development team decided to go for a rigid frame system with round tubes. The teachers and pupils at Ås high school were also interested in making the compartment by using the press-forming bend tool to make the casing. This actually took me back to my first ideas shown in Figure 5-17. Since the production methods involved press forming there are challenges in making the cases out of one complete piece with a separate lid. The main case needed to be split in two halves, and welded or riveted together. To create a watertight seal I decided to get them welded together as the case did not have a significant contribution to the frame structures, although the casing will contribute a bit by stiffening the frame.

Unfortunately, the workshop did not have the right tools to design the electronic case with a double flange, but a single flange might be just as great choosing a good rubber seal. Figure 5-21 shows a variety of rubber seal strips.

Figure 5-21. A variety of rubber seal strips for putting onto a flange for water sealing.

To make the seal tight and waterproof, an IP65 quarter turn locking mechanism from KIPP is used. This involves the locking mechanism K0522.20181 and tongue K0523.135X205 shown in Figure 5-22.

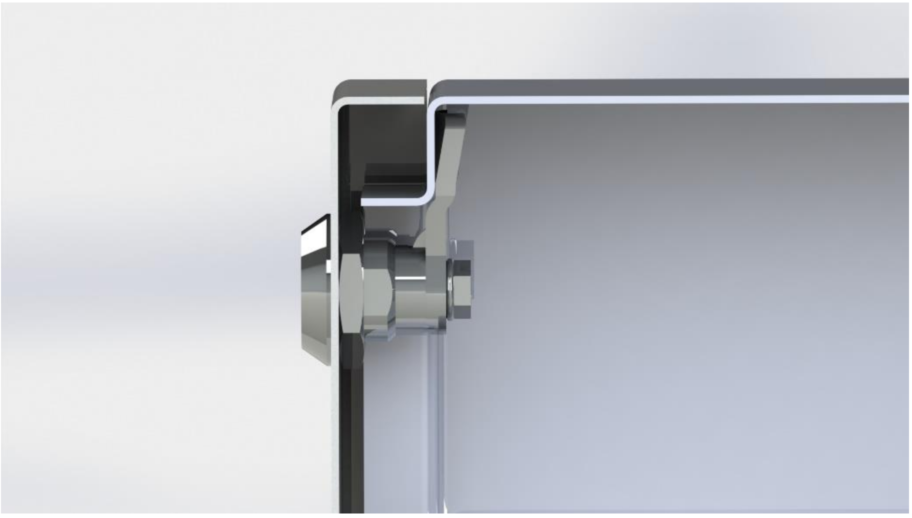


Figure 5-22. Cross section of the final solution of an aluminum enclosure and locking mechanism from KIPP. Notice the spacing between the lid and the lip for rubber seal fitting.

5.5. Tool Equipping

Tools are an essential piece of the robot. Due to a limited amount of time, I will show some examples for tool equipment and exchange. Except manual installation with tube clamps, Figure 5-23 shows a rail system, where the tool could automatically be entered on the robot. It does however demand a locking device to hold it in place.

Figure 5-23. Using rails on the lower frame, the tool can be centered onto the rails with the help of the bended rail ends shown on the rendering.

Watching more closely a V-shaped roller could be a solution for the rail, see Figure 5-24. In addition, an open clamp like on a scaffold could be a solution that can also provide some stiffness.

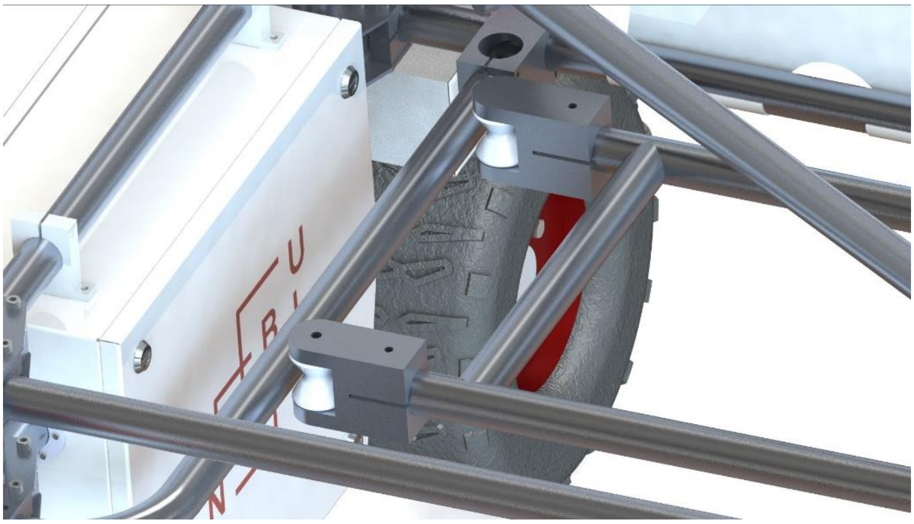


Figure 5-24. One solution is to mount the tools on a standard frame. Here is a solution with V-rollers for easy reduced friction during tool docking.

5.6. Other Designs

The extremely flexible frame design opens for a lot of possibilities. This include a Three-wheel version, or a slim version for more confined areas and greenhouse alleys.

Figure 5-25. This is the collection and some of the possibilities for the Thorvald project.

5.7. Calculations and simulations

5.7.1. General calculations

By quasi-static methods of calculations, it is recommended to add a vehicle factor (VF) to compensate for dynamic loads. For smaller vehicles, recommended factor is set to 2 [47]. This means multiplying the vehicle weight by two. The total weight of the robot including payload is 400 kg. Using the equation (5.4) below, we can estimate the weight on wheels - N_w.

$$F_N = \frac{m \cdot g \cdot VF}{4} \tag{5.4}$$

$$F_N = \frac{400\ kg \cdot 9.81 \frac{m}{s^2} \cdot 2}{4} = 1962\ N$$

$$F_N = 1962\ N$$

Figure 5-26. Case while driving in the normal direction.

The electric motor operates with a 1.57 Nm nominal and a 3.14 Nm maximum torque. The gearbox has a 96% efficiency and gear ratio of 7:1. The timing belt has a 4:1 gear ratio, which typically has up to 98% efficiency. The maximum wheel torque calculated as:

$$T_{w,max} = T_{m,max} \cdot i_G \cdot i_B \cdot \eta_G \cdot \eta_B \tag{5.5}$$

Where:

$T_{w,max} =$	Maximum wheel torque
$T_{m,max} =$	Maximum motor torque
$i_G =$	Gearbox gear ratio
$i_B =$	Timing belt gear ratio
$\eta_G =$	Gearbox gear efficiency
$\eta_B =$	Timing belt efficiency

$$T_{w,max} = 3.14\ Nm\ \cdot 7 \cdot 6 \cdot 0{,}96 \cdot 0{,}98 = 124\ Nm$$

$$T_{w,max} = 124\ Nm$$

To find the load on the hinges, there are two stressful situations to consider. Case 1, normal load while driving forward as in Figure 5-26, and Case 2, load while driving sideways as in Figure 5-27.

5.7.2. Case-Based Calculations

Case 1:

In Case 1, the robot has normal forward driving conditions, but while pulling heavy objects, or one set of wheels stuck. The propulsion is limited due to the weight of the vehicle and friction coefficient between the rubber wheel and the ground, see equation

(5.6). The Friction coefficient (μ_k) between rubber and concrete is about 0.8 according to Tipler, Mosca [23].

$$F_p = \mu_k \cdot N \tag{5.6}$$

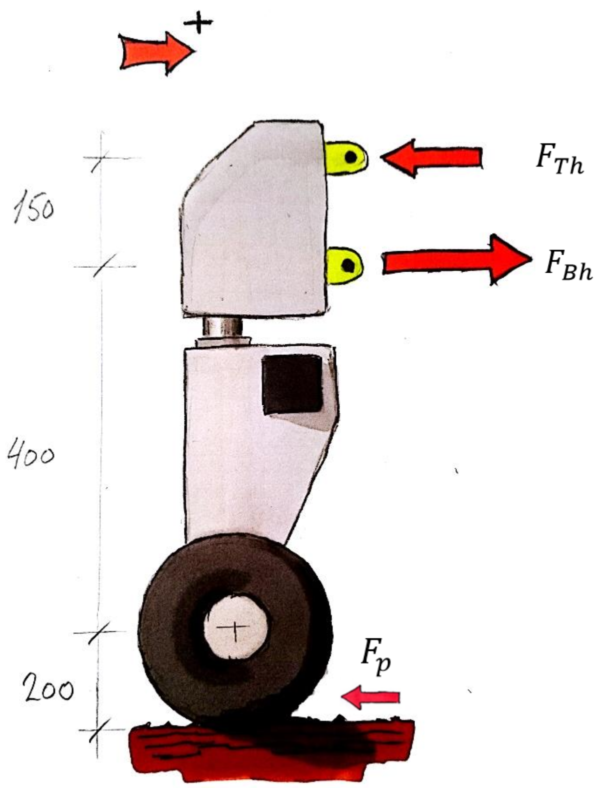
$$F_p = 0.8 \cdot 1962\ N = 1570\ N$$
$$F_p = 1570\ N$$

The propulsion force is the maximum possible force the wheel can produce with the given weight load applied. For comparison we can find the wheel torque required to produce the same amount of force as the maximum possible propulsion.

$$T_{w,req} = r_w \cdot F_p \tag{5.7}$$

$$T_{w,req} = 0{,}2\ m\ \cdot 1570\ N = 314\ Nm$$
$$T_{w,req} = 314\ Nm > 124\ Nm$$

The above calculations conclude that the motor torque is lower than the ground friction allows. When doing further calculations I will still use the propulsion caused by friction rather than motor torque. This is because future editions could be reequipped with a more powerful motor, and the friction force is the closer to a propulsion limitation. In addition, in case of a sudden wheel block or braking, it is momentarily possible to achieve 1570 N of force. By using in Newton’s third law, we find:



$$\Sigma M = 0 \tag{5.8}$$

$$\Sigma M_{Th} = F_p \cdot \left(r_w + l_m + \left(\frac{l_h}{2}\right) \right) + F_{Bh} \cdot l_h = 0$$

$$F_{Bh} = \frac{1570 \cdot 0.75}{0.15} = 7850\ N$$

$$F_{Bh} = 7850\ N$$

The force exceeded on the top hinges are 7850 N. With two top hinges, this is equivalent of 3925 N per hinge.

$$\Sigma F = 0 \tag{5.9}$$

$$F_p - F_{Bh} + F_{Th} = 0$$

$$F_{Th} = 7850\ N - 1570\ N = 6280\ N$$

$$F_{Th} = 6280\ N$$

The forces exceeded on the bottom hinges are 6280 N. With two bottom hinges, this is equivalent to 3140N per hinge

Case 2:

In this case, the wheel is turned 90 degrees relative to the hinges. This causes a rotational moment exceeding on the hinges as shown in Figure 5-27 with blue vectors. In addition, the hinges expose of a reactional shear force. By the use of Newton's third law, we calculate:

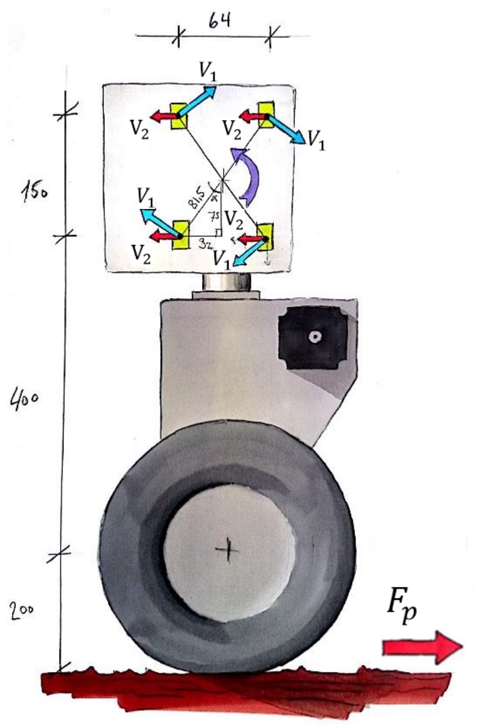


Figure 5-27. Hinge load while driving sideways.

$$\Sigma M = 0 \tag{5.8}$$

$$F_p \cdot \left(r_w + l_m + \left(\frac{l_h}{2}\right)\right) - 4V_1\sqrt{\left(\frac{l_h}{2}\right)^2 + \left(\frac{l_w}{2}\right)^2} = 0$$

$$F_p \cdot 675\ mm - 4V_1\sqrt{75\ mm^2 + 32\ mm^2} = 0$$

$$675F_p \ = 326V_1$$

$$V_1 \approx 2F_p = 3251\ N$$

By using the tangent formula, we can find the angle α between the vertical center and the hinge.

$$\tan\alpha = \frac{Opposite}{Adjacent} \tag{5.10}$$

$$\alpha = \tan^{-1}\left(\frac{\left(\frac{l_w}{2}\right)}{\left(\frac{l_h}{2}\right)}\right)$$

$$\alpha = \tan^{-1}\left(\frac{32}{75}\right) \approx 23°$$

Because the V_1 decomposition is uniform to the hinge triangle, the angle α is equivalent. Next, we find the x- and y-values of V_1 vector.

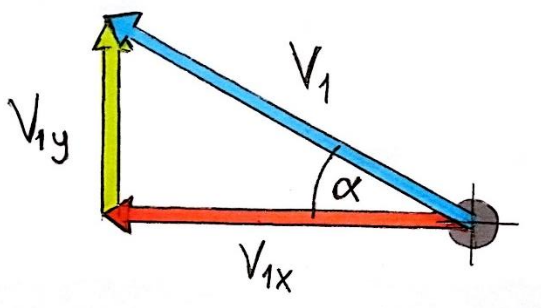


Figure 5-28. Decomposition of the V_1 force on the lower left hinge.

$$V_{1x} = V_1 \cos\alpha$$

$$V_{1x} = 2F_p \cdot \cos 23° = 1.84\ F_p$$

$$V_{1x} = 2889\ N$$

$$V_{1y} = 2F_p \cdot \sin 23° = 0.78\ F_p$$

$$V_{1y} = 1225\ N$$

To find the largest resultant force in Figure 5-27, we need to find the shear force V_2, marked as red in the same figure by using equation (5.11).

$$\mathrm{V_2} = \frac{\mathrm{F_p}}{4} = 0.25\ \mathrm{F_p} \tag{5.11}$$

$$V_2 = 0.25\ F_p$$

$$V_2 = 393\ N$$

The bottom two hinges have the largest resultant forces. Equation show us how we find the resultant forces.

$$V_R = \sqrt{{V_{1y}}^2 + (V_{1x} + V_2)^2} \tag{5.12}$$

$$V_R = 1570\ N \cdot \left(\sqrt{0.78^2 + (1.84 + 0.25)^2}\right) = 3616\ N$$

$$V_R = 3502\ N$$

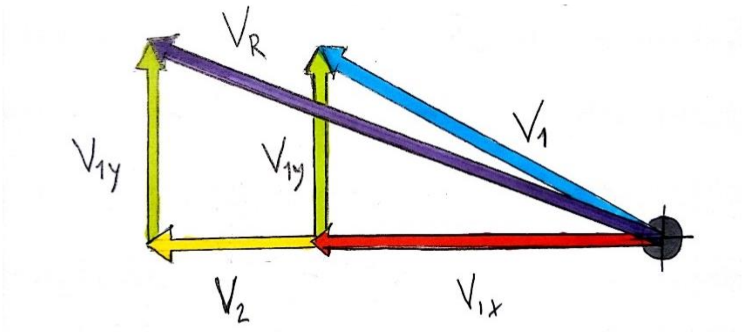


Figure 5-29. Reactional force on lower left hinge.

For the correct choice of hinge glide bearings, the most important values are the sum of the axial V_{1x} and V_2, and the radial V_{1y} forces.

Top view of case 2 shown in Figure 5-30 reveals the propulsion force F_p exerts radial forces on the hinges. The radial outer hinge force F_{OH} and inner hinge force F_{IH} are illustrated in the figure below. By using Newton's third law, we find the forces of the outer hinge.

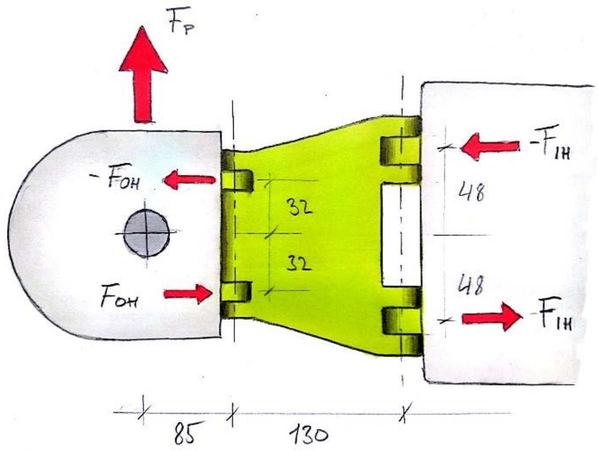


Figure 5-30. Top view of forces acting on the hinges. The propulsion force affects the outer and inner hinge forces. All values in mm.

$$\Sigma M = 0 \tag{5.8}$$

$$F_p \cdot 85\ mm - F_{OH} \cdot 64\ mm = 0$$

$$F_{OH} = \frac{1570\ N \cdot 85\ mm}{64\ mm} = 2085\ N$$
$$F_{OH} = 2085\ N$$

The radial forces of the outer hinges are 2085 N. The forces of the inner hinge are calculated the same way.

$$\Sigma M = 0 \tag{5.8}$$
$$F_p \cdot 215\ mm - F_{IH} \cdot 96\ mm = 0$$
$$F_{IH} = \frac{1570\ N \cdot 215\ mm}{96\ mm} = 3516\ N$$
$$F_{IH} = 3516\ N$$

The Radial forces of the inner hinge bearings are 3516 N. Further, we need to find the resultant radial force between the F_{OH} and the V_{1y} as shown in Figure 5-31.

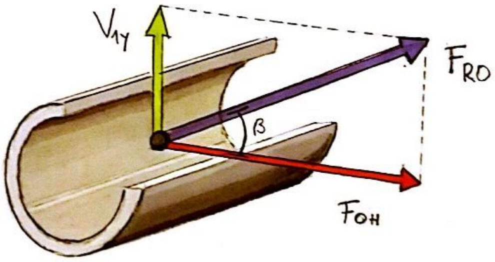


Figure 5-31. Force components in a bearing, including the resultant force.

$$\tan\beta = \frac{Opposite}{Adjacent} \tag{5.13}$$
$$\beta = \tan^{-1}\left(\frac{V_{1y}}{F_{OH}}\right)$$
$$\beta = \tan^{-1}\left(\frac{398\ N}{2085\ N}\right) \approx 10.7°$$
$$F_{RO} = \frac{2085\ N}{\cos 10.7°} = 2122\ N$$
$$F_{RO} = 2122\ N$$

The maximum radial force on the outer hinge is 2122N. For the inner hinges same rules apply. However, for case 2, the moment of area is bigger because of a higher distance between the hinges. Instead of recalculating forces from Figure 5-27, I will calculate the radial forces with the same V_{1y} value. This will give me a larger value.

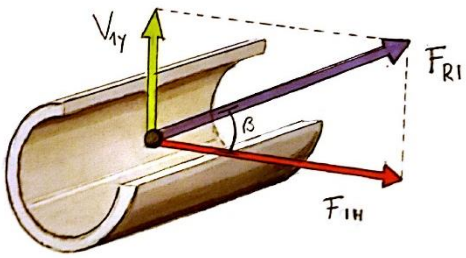


Figure 5-32. Force components in a bearing, including the resultant force.

$$\tan \beta = \frac{Opposite}{Adjacent} \tag{5.13}$$

$$\beta = \tan^{-1}\left(\frac{V_{1y}}{F_{IH}}\right)$$

$$\beta = \tan^{-1}\left(\frac{398\ N}{3516\ N}\right) \approx 6.4°$$

$$F_{RI} = \frac{3516\ N}{\cos 6.4°} = 3538\ N$$

$$F_{RI} = 3538\ N$$

The radial resultant, F_{RI} value is higher than the correct value. By using V_{1y} value, we achieve a low angle of 6.4°, which means that we can avail the use of the small angle rule applicable for angles below 15° according to Mosca [23]. Below this value, the approximation becomes increasingly more accurate. This means:

$$F_{RI} \approx F_{IH} = 3516$$

To find a proper gliding bearing for the hinges, the calculation of F_{RI}, which describes the largest radial hinge bearing force is used to choose the correct bearing in the next section.

5.7.3. Choice of Bearings

To achieve a low friction suspension hinge support that minimize the wear of the suspension components, I need to find a suitable glide bearing, or bushing. There are a number of advantages by the use of bearings instead of direct contact between steel pin and aluminum. One is that aluminum has a lower abrasive resistance than steel, so the aluminum gets sacrificed, causing loose connections, and even risk of breakage.
Brass is a common bushing material with certain alloys that is self- lubricating, but this causes another problem. Aluminum gets sacrificed by galvanic differences in combination with steel or brass. I have been in contact with TESS AS, that recommends bushings from SKF, a Swedish bearing manufacturer. They produce a certain bearing that is suitable between aluminum and steel components. These bushings are the PPMF-series that in made of a composite material shown in Figure 5-33, which means no galvanic corrosion on the aluminum components,.

Figure 5-33. The SKF PPMF-series of composite bushings.

Based on the needs, calculations and conversations, I've got a personal recommendation of the PPMF 14 mm outer diameter, and 12mm inner diameter bushings [48]. Table 5-2 contains the bearing characteristics properties.

Table 5-2. This table contains characteristics and recommendations of the PPMF bushing series [49].

Characteristics	
Permissible load (dyn/stat), N/mm^2	40 / 80
Permissible sliding velocity, m/s	1,0
Friction coefficient μ	0,06 .. 0,15
Temperature range, °C	–30 .. +110
Application recommendations	
Shaft tolerance	h8 – h9
Housing tolerance	H7
Shaft roughness R_a, μm	0 .. 0,8
Shaft hardness, HB	100 – 300

5.7.4. Tube friction connections

The modular tube feature of this platform consists of tube clamps, which hold the frame together, see Figure 5-34. To estimate the amount of force needed to hold the tube in place, we use the formula of bolt friction connection [50]. The friction coefficient between aluminum and aluminum is 1.05.

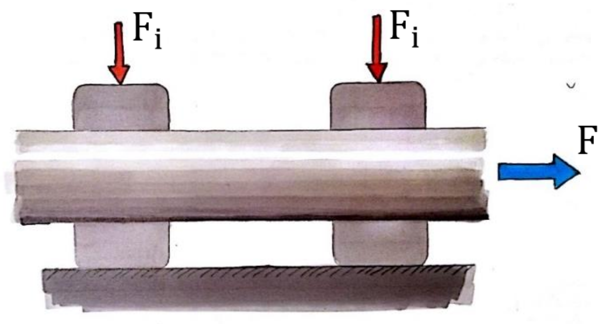


Figure 5-34. Simplified illustration of the tube friction connection.

$$F_i = \frac{F \cdot n_g}{n \cdot m \cdot \mu} \tag{5.14}$$

Where:
F_i = Pre-tension per bolt
$F =$ Pulling force (F_p)
n_g = Safety factor of gliding
n = Number of bolts
m = Number of surfaces that translates friction
μ = Friction coefficient

$$F_i = \frac{7850\ N \cdot 4}{4 \cdot 4 \cdot 1.05} \approx 1870\ N$$
$$F_i \approx 1870\ N$$

The required bolt pre-tension is about 1870 N per bolt. Since aluminum is expanding and shrinking more than the steel bolts in temperature changing conditions, it is necessary with a high safety factor. According to ISO-standard [51], an 8.8 grade M8 bolt has a tensile proof strength of 500 N/mm^2 and tensile strength of 800 N/mm^2. Using the bolt stress area of 36.6mm^2 we calculate bolt initial stress.

$$\sigma_i = \frac{1870N}{36.6\ mm^2} = 51\ N/mm^2$$
$$\sigma_i = 51 \frac{N}{mm^2} << 800\ \mathrm{N/mm^2}\ \rightarrow\ OK$$

5.7.5. Hinge calculations

Hinge pin

To see if the hinge pin hinge connections are strong enough, we can calculate the hinge pin shear stress by the standard equation (5.15) applicable per shear connection.

$$\tau = \frac{F}{n \cdot A} \tag{5.15}$$

Where:
$\tau =$ Shear stess [N/mm^2]
$n =$ Number of shear connections
$A =$ Area of hinge ($\pi \cdot r^2$) [mm^2]

To calculate the highest amount of shear stress, the fewest amount of shear connections are on the upper hinge, with its two shear connections.

$$\tau = \frac{6280\ N}{2 \cdot \pi \cdot 6^2} = 28\ N/mm^2$$
$$\tau = 28\ N/mm^2$$

By using stainless steel AISI 314 material for the hinge pin with a yield strength of 310 N/mm^2, the shear calculations are way below permanent deformation.

$$\tau = 28\ N/mm^2\ <<\ 310\ N/mm^2\ \rightarrow OK$$

Hinge simulation

To see if the hinges are strong enough, I have simulated the weakest hinge using ANSYS workbench, FEM-analysis computer program. To get a more correct simulation, a deflation method is used for meshing the surrounding hinge-holes. Figure 5-35 shows the simulation with the maximum of about 80 N/mm^2, which is below the yield strength of 170 N/mm^2.

$$\sigma = 80\ N/mm^2 << 170 N/mm^2 \rightarrow\ OK$$

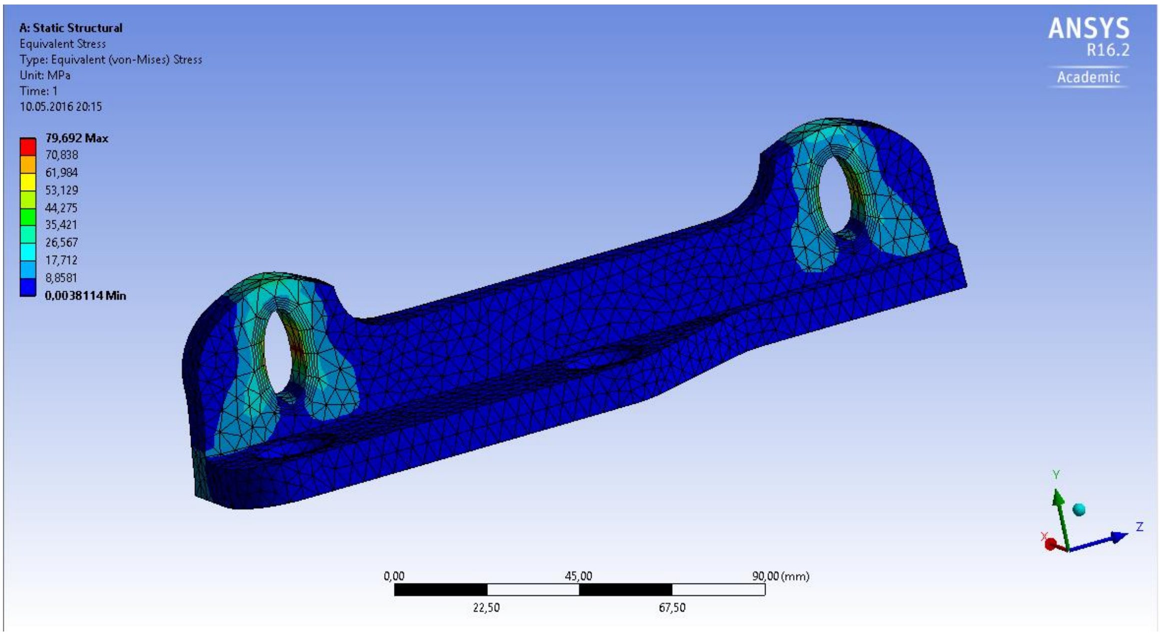


Figure 5-35. ANSYS hinge simulation with the result of about 80 N/mm^2.

5.7.6. Frame calculations

To see if the following simulations are more or less correctly setup, its necessary to do some hand calculations to compare with. To find the maximum amount of forces acting on the frame, imagine the upper frame gets statically fixed driving forward, either by pulling something or getting stuck by an object. The Forces in the wheels will cause a 7850 N pulling force on the lower frame as in Figure 5-36.

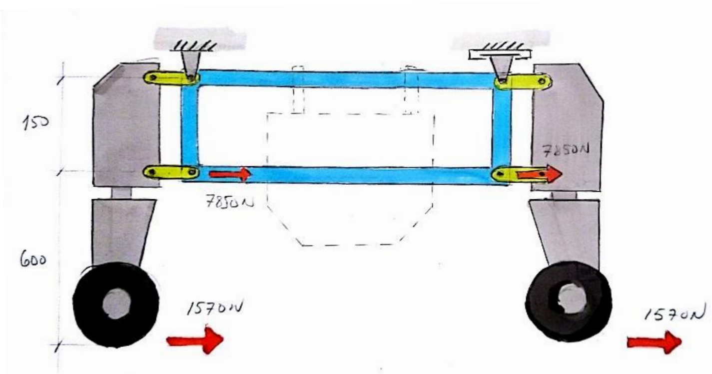


Figure 5-36. Worst case scenario, Case 1, where the wheel moments affect the frame if stuck on upper frame while pulling tools etc. Normally tools are mounted on the lower frame, causing lower stress.

Figure 5-37 shows a simplified diagram with the reaction forces acting.

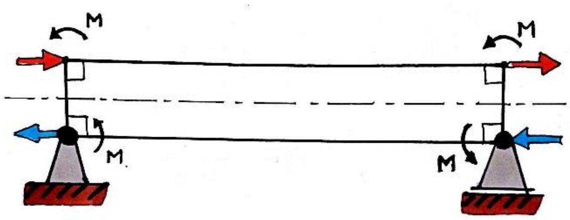


Figure 5-37. Simplified illustration of Figure 5-36 that shows moments appear in upper and lower pairs.

For hand calculation simplicity, we can do the following estimation in Figure 5-38, and calculate the deflection using equation (5.16).

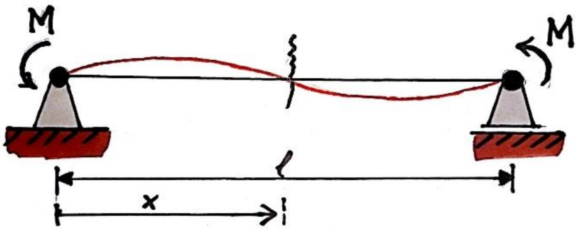


Figure 5-38. Using the moments for the simplified lower frame, we can calculate deflection and stress.

$$y = \frac{M(\frac{l}{2})x}{6EI} \cdot (1 - \frac{x^2}{(\frac{l}{2})^2}) \tag{5.16}$$

$$y = \frac{590\ Nm\ \cdot 0.35 \cdot 0.175}{6 \cdot 70 \cdot 10^{10} N/m^2 \cdot 67.45 \cdot 10^{-9} m^4} \cdot (1 - \frac{0.175^2}{0.35^2}) \cdot 10^3 [mm]$$

$$y = 0.96\ mm$$

Stress:

To find the maximum bending stress at the deflection above, we use equation (5.17) below.

$$\sigma = \frac{M}{W} \tag{5.17}$$

$$\sigma = \frac{M}{\left(\frac{\pi}{32} \cdot \frac{D^4 - d^4}{D}\right)}$$

$$\sigma = \frac{590\ Nm * 10^3}{\left(\frac{\pi}{32} \cdot \frac{40^4 - 33^4}{40}\right)} = 175\ N$$

$$\sigma = 175\ N$$

By simulating a simplified nacelle frame with SolidWorks Simulation, we can see if the hand calculation values are nearby the values in Figure 5-39 and Figure 5-40.

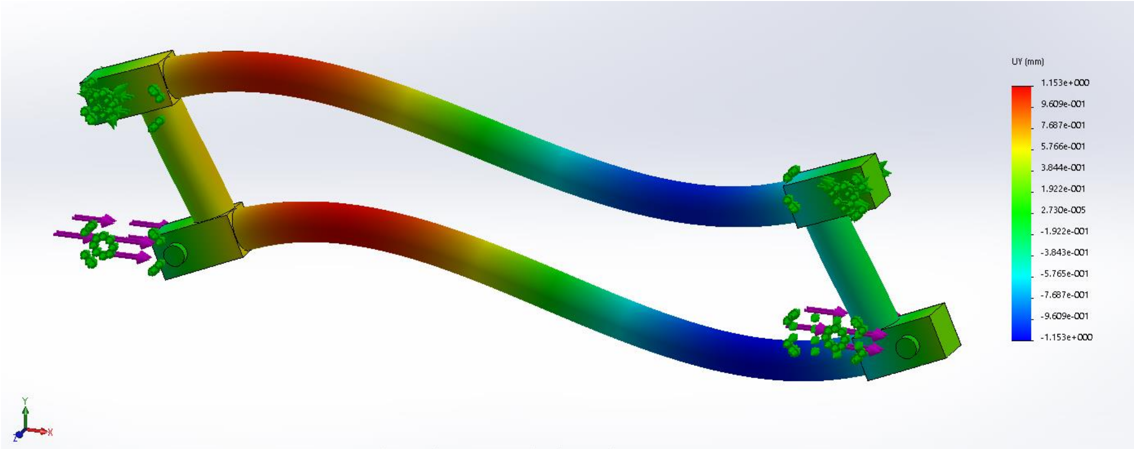


Figure 5-39. This figure shows the amount of deflection in the Y-direction. Red are the most deflected in a positive vertical Y-direction. Max deflection is 1.15 mm.

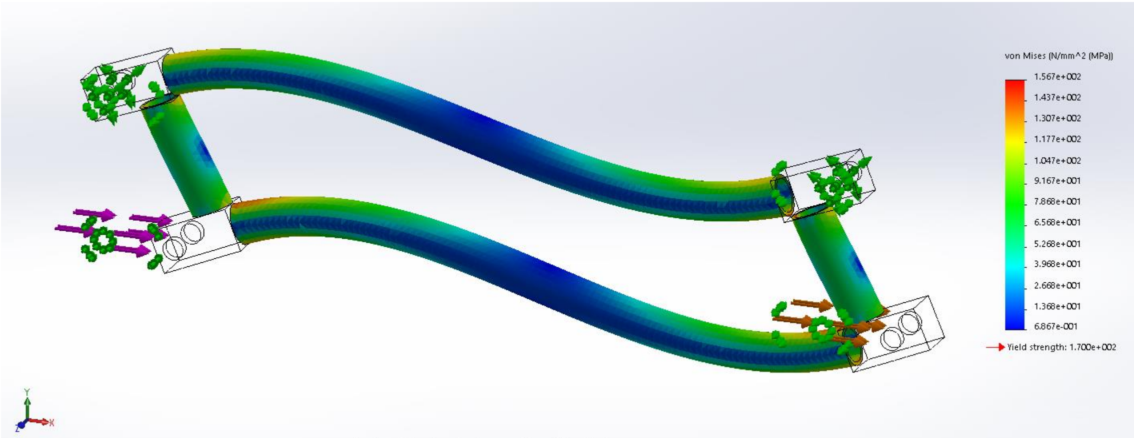


Figure 5-40. This figure shows the amount of stress in the tubes. Red areas are the most stressed, and has maximum bending stress of 157 MPa. Maximal stress allowed without permanent damage is 160 MPa.

The next SolidWorks plot uses the same forces as in the examples above, but with the entire frame, and an attempt to stiffen the frame using a V-shaped bar shown in Figure 5-41 and Figure 5-42.

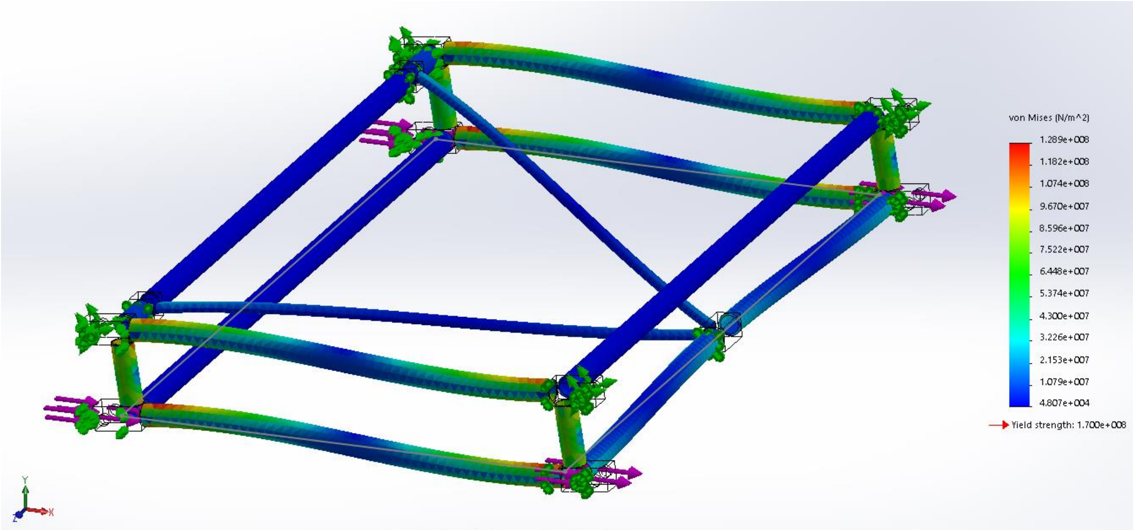


Figure 5-41. A similar SolidWorks simulation plot of the whole frame with attempt of V-shaped stiffening bars. Results of 130 MPa show little, or no improved stiffness.

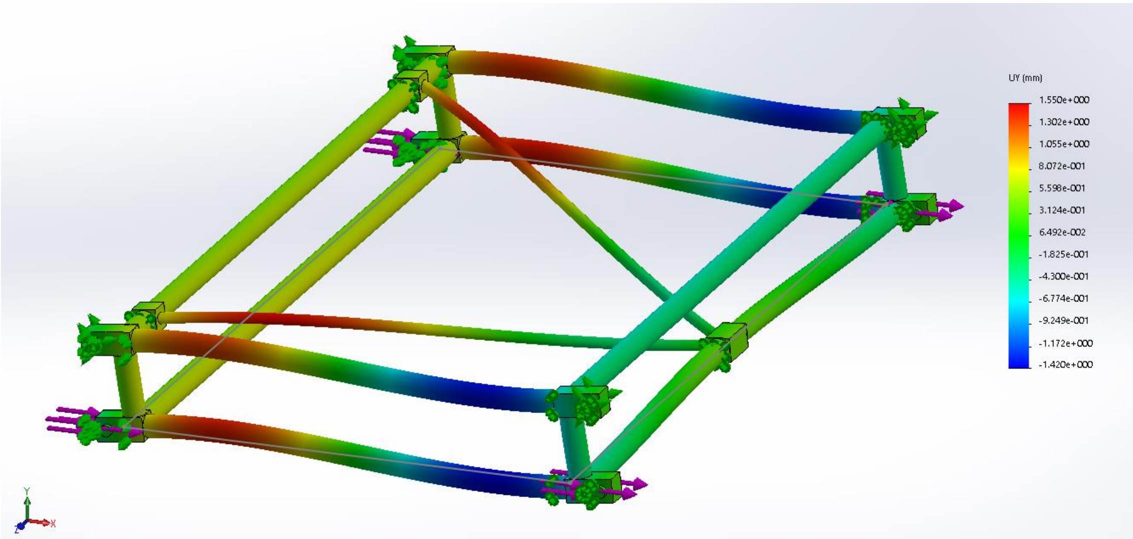


Figure 5-42. The SolidWorks deflection plot of the whole frame, showing a deflection of 1,6 mm with the V-shaped bars.

SolidWorks simulations do have a 3D model based FEM analysis, which also calculates other surrounding elements. If the simulation of the beams are the only interesting data, it is better to use the classical ANSYS that uses key points and beam element. This type of simulation reduces disturbances of the surrounding structures and keeping the singularity of the elements. Figure 5-43 shows an ANSYS classical plot with forces similar to the nacelle frame.

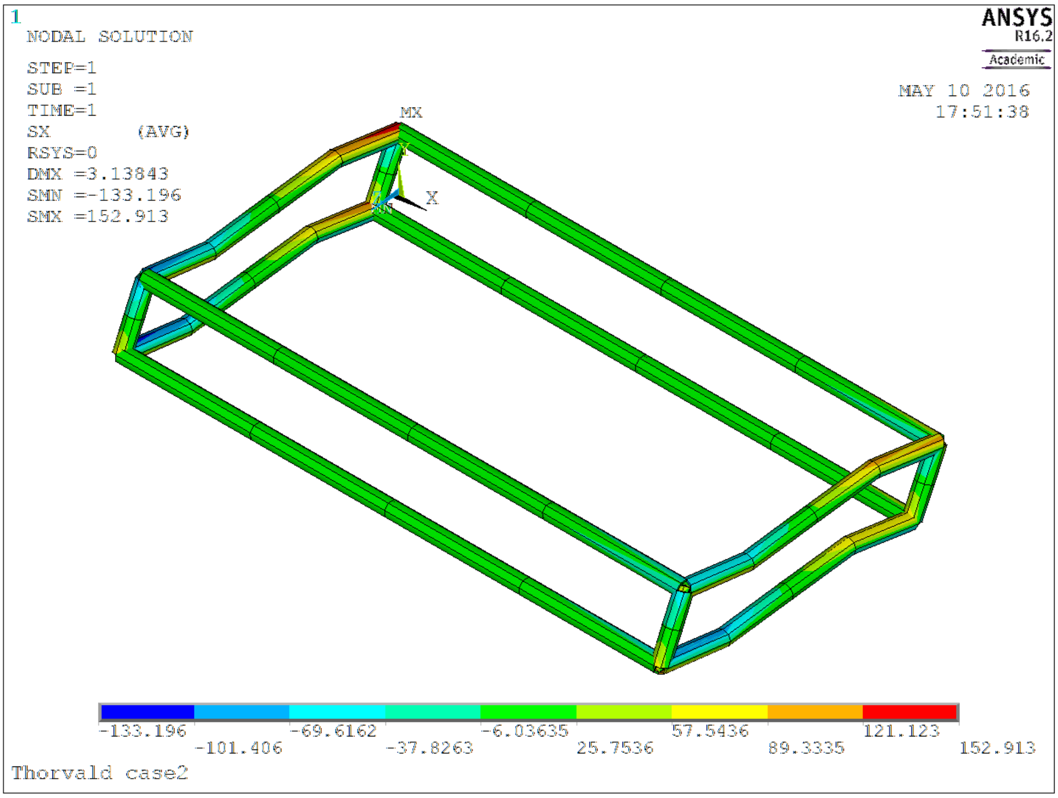


Figure 5-43. ANSYS key point based simulation plot enabling better nodal supports. Results are put in the table below.

Figure 5-44 shows an ANSYS plot with the forces acting while vehicle is driving sideways. The results show us that the stresses are similar as in the normal driving direction in the above simulations, while the vertical deflection of 7 mm is larger.

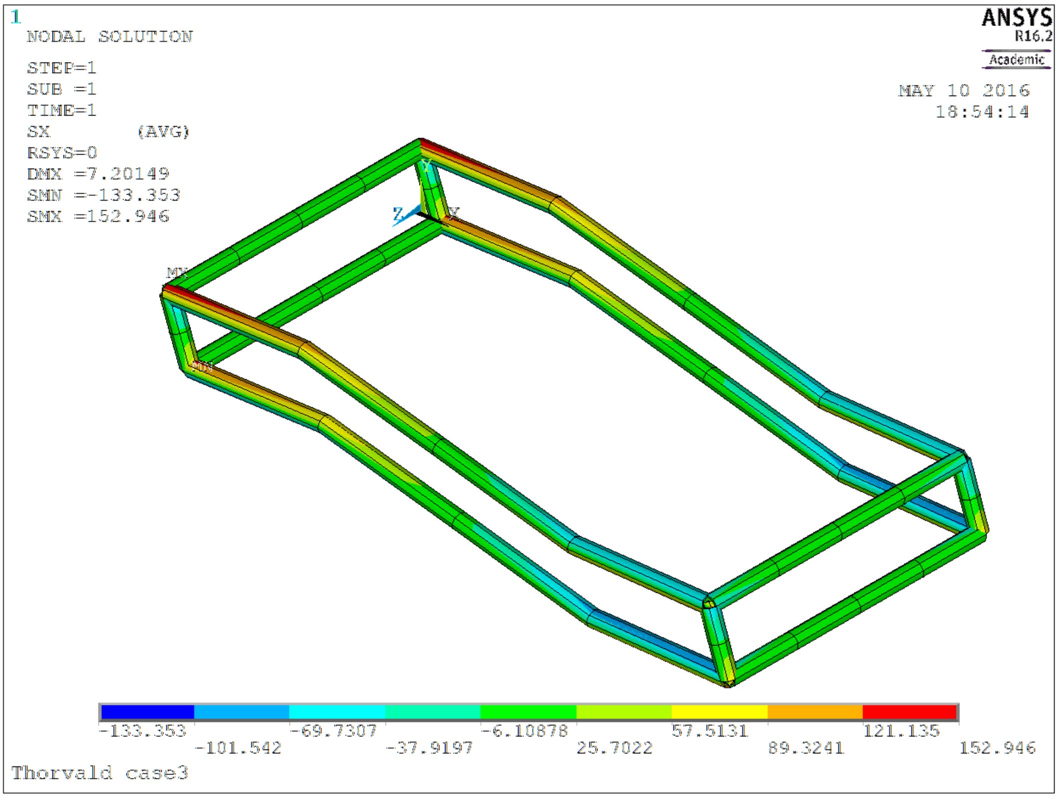


Figure 5-44. Plot of vehicle while driving sideways under similar conditions, notice the similar stresses as in previous plots.

To get an indication and efficiency of the frame overall stiffness with a cross directional bar, I have simulated a ANSYS plot in Figure 5-45. This plot is for an informational purpose only, and is not compared with other situations.

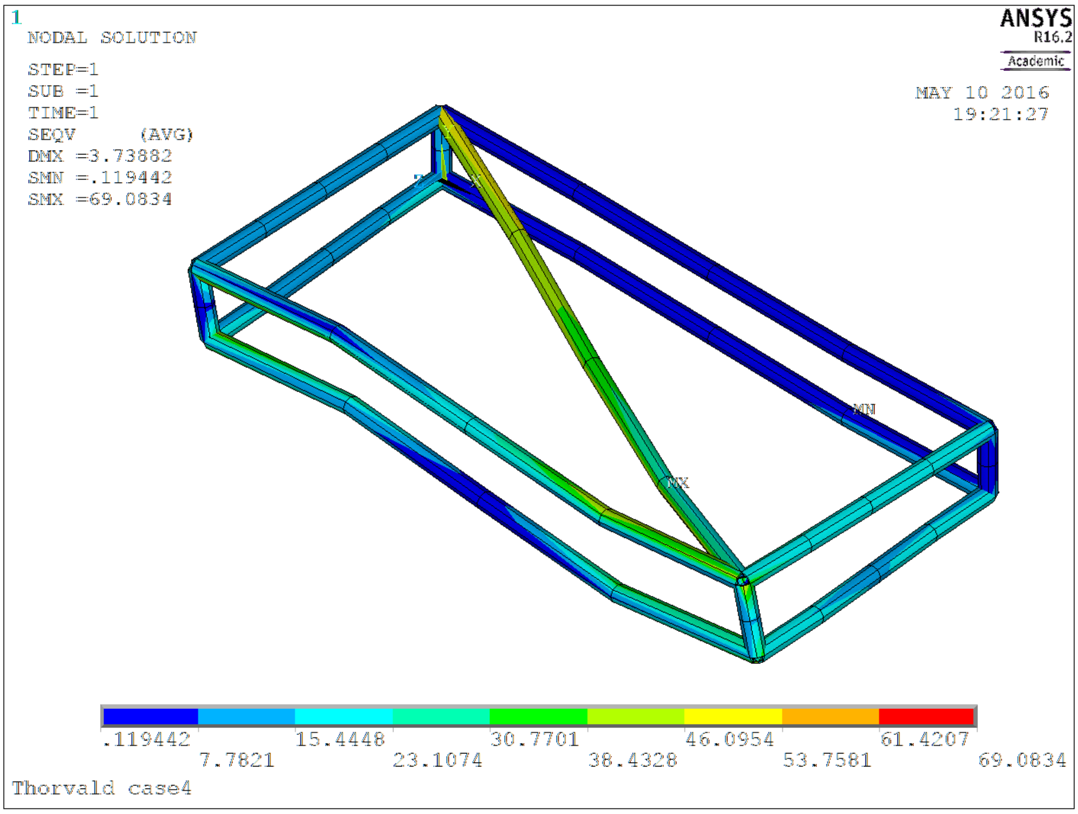


Figure 5-45. Example of plot with a cross directional stiffener driving sideways with front wheels stuck.

Table 5-3. An overview of values in different cases.

	Simple			***Full Frame***			***Sideways***		
Method	**Deflection [mm]**		**Stress [MPa]**	**Deflection [mm]**		**Stress [MPa]**	**Deflection [mm]**		**Stress [MPa]**
	y	**x**		**y**	**x**		**y**	**x**	
ANSYS	-	-	-	-	3.1	153	7	-	153
SolidWorks	1.17	2.22	157	1.55	2.4	129	-	-	-
Manual	0.96	-	174	-	-	-	-	-	-

These values are simulated, calculated and compared with the properties of the aluminum 6060 T6. The aluminum alloys as a yield strength of 170 MPa. The values are below the yield strength values, suggesting that there are no permanent damages to the frame aluminum tubes. These results will be discussed further in the conclusion section of Part 1.

5.7.7. Calculation Conclusion and Discussion

By calculating the most exposed parts of the frame, suspension and bearings, these calculations and simulations show that the stress values are below the material maximum stress values. I can conclude that the frame and suspensions are ready for production and assembly.

With this modular design, I suggest experimenting with different configurations of stiffing features like lateral bracing elements combined with tool changing solutions, to find the best suitable solution.

5.8. Product architecture

The friction based tube connections allow complete adjustments of wheel base, and a minimum of length is limited to the electronic compartment. Aluminum allows weight reduction over a similar steel construction.

Figure 5-46. Fully assembled robot with visible frame, without covers.

5.8.1. Frame

The frame is divided into two nacelles in a normal configuration, connected by tubes and free choice of stiffening options.

Figure 5-47. The robot are divided into two nacelles connected by a frame.

5.8.2. Nacelle

The nacelle consists of the wheel modules, suspension, nacelle frame and electric compartment.

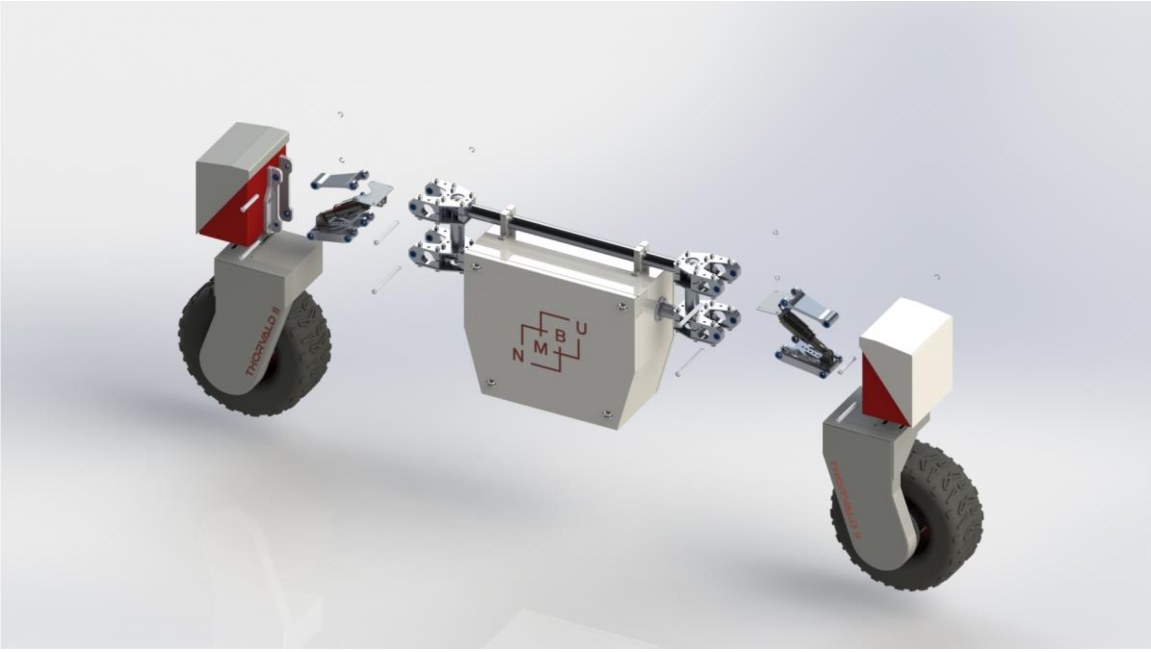


Figure 5-48. The nacelle is consisting of the wheel module assemblies, suspension and center nacelle frame.

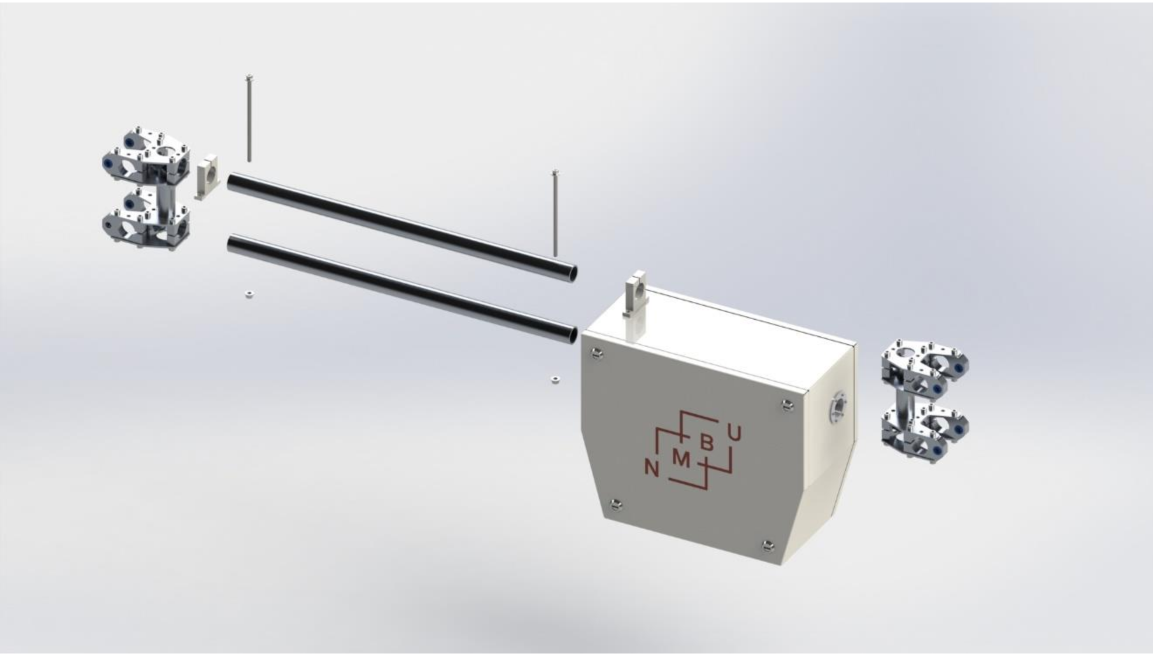


Figure 5-49. The center nacelle containing the electronic compartment, brackets, T-connections and thread bars for connecting upper and lower nacelle frame tubes.

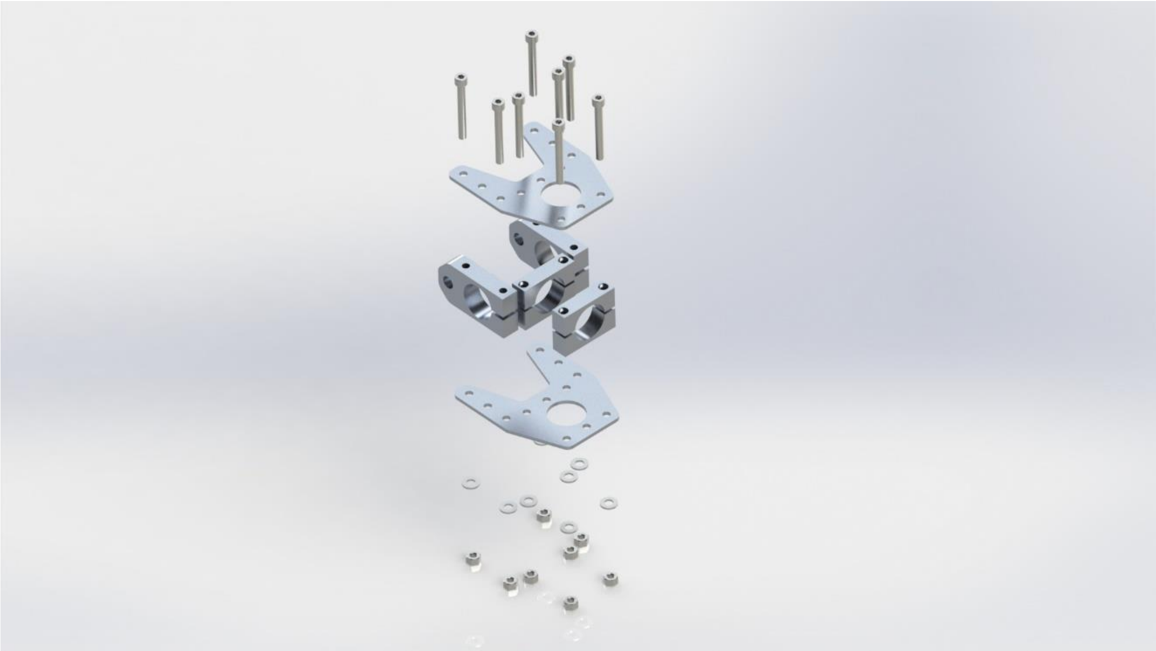


Figure 5-50. T-connection assembly, containing tube clamps, hinged tube clamps, sandwich T-bracket plates and bolts.

5.8.3. Suspension

The suspension glide bearings, or bushings are dependent on a H7 hole fitting in the wheel module brackets, suspension arms and hinge tube brackets.

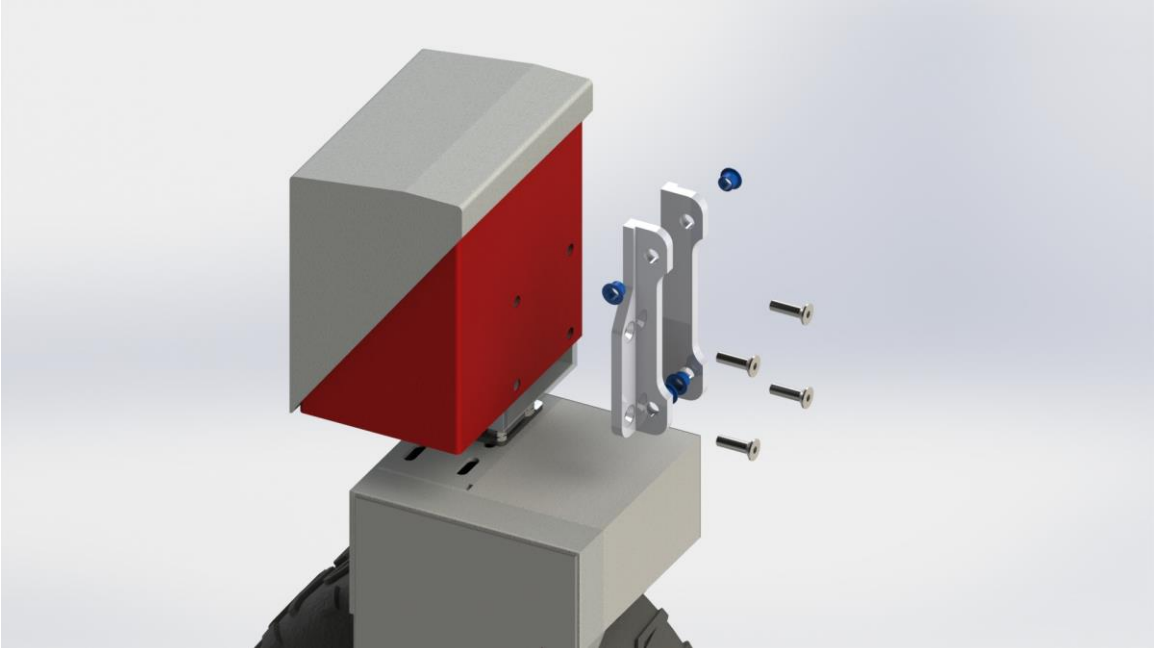


Figure 5-51. The suspension brackets are bolted onto the wheel module, with the belonging glide bearings.

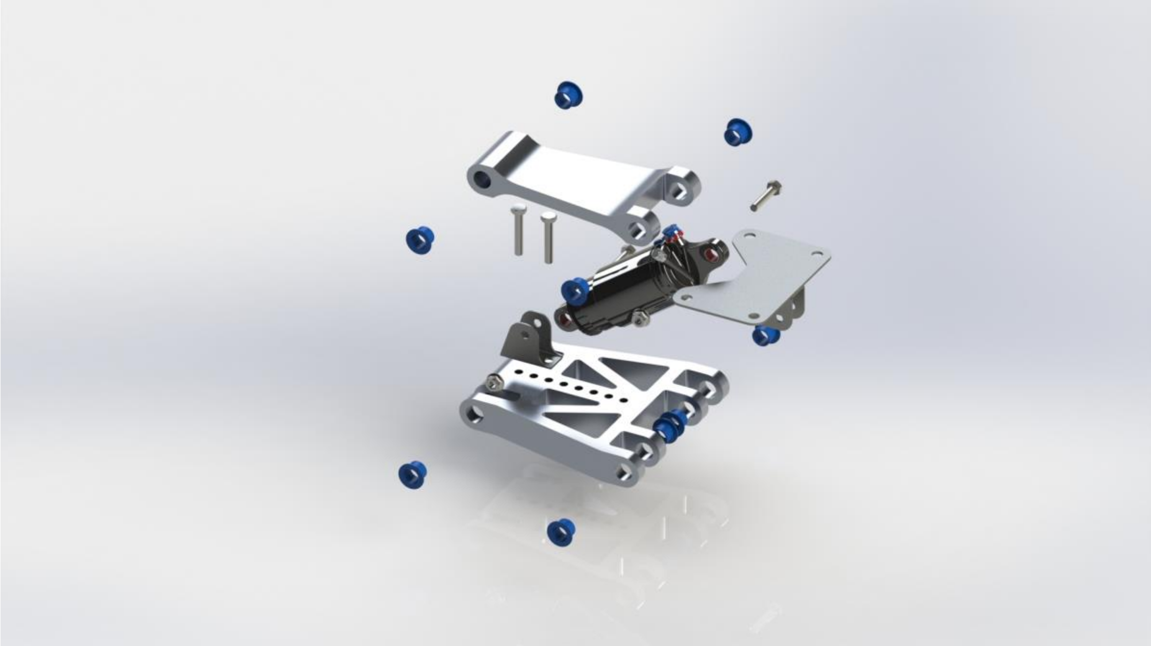


Figure 5-52. The suspension assembly, consisting of bearings, suspension arms, dampers, and damper hinges.

5.8.4. Electronic compartment

The electric compartment box shells are welded together. Other parts are clamped together, like the electronic shelf and lid locking mechanism.

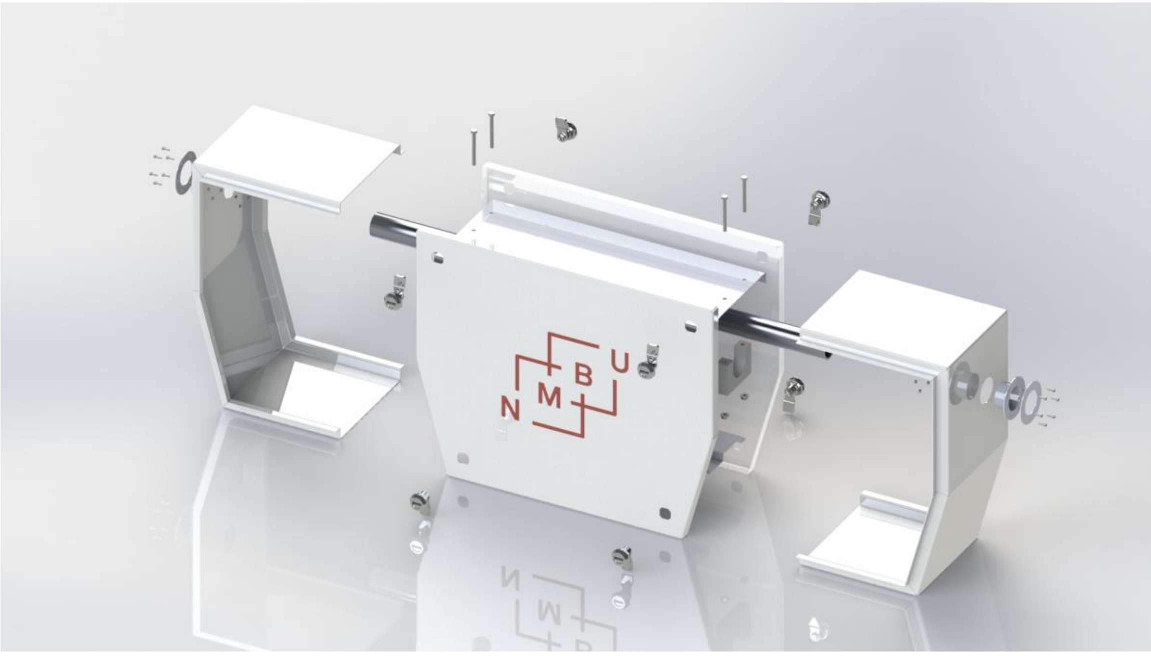


Figure 5-53. The outer electronic compartment shells are welded together and the lids are mounted with a locking device. The insides contains of the frame tube, shelf, bottom drain plate, and its mounting brackets.

6. Building process

6.1. Production process

The production process of the frame and suspension is a combination of help from the workshop in Ås high school, NMBU workshop and Dynatec SMV in Askim.

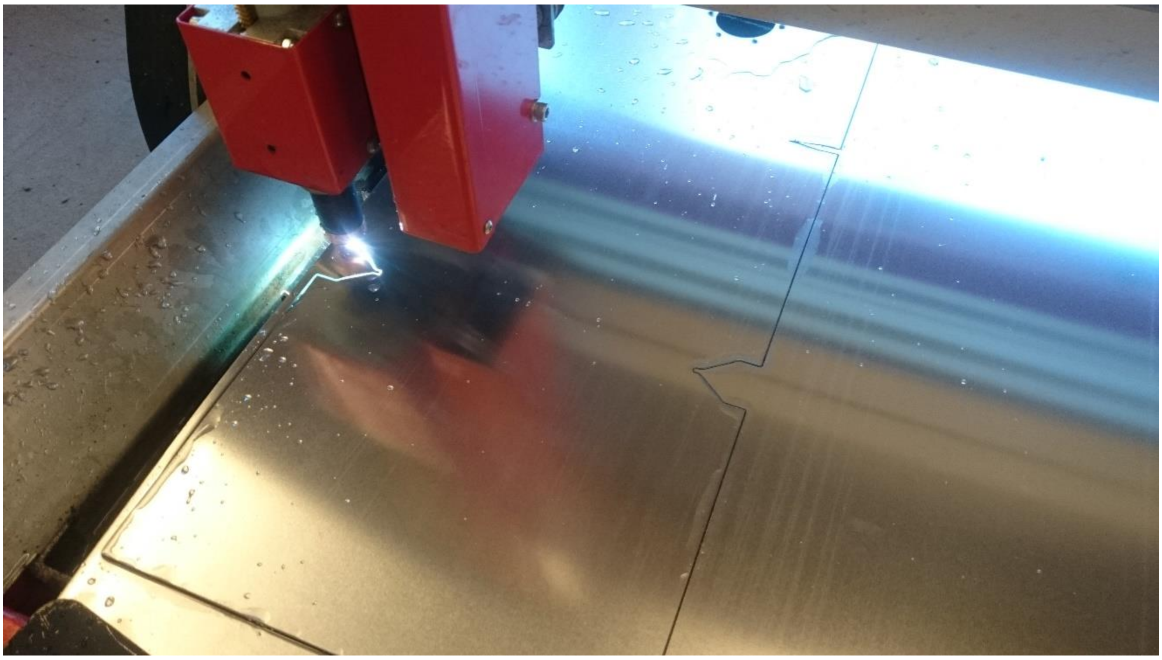


Figure 6-1. Plasma cutting process of the half piece of the box.

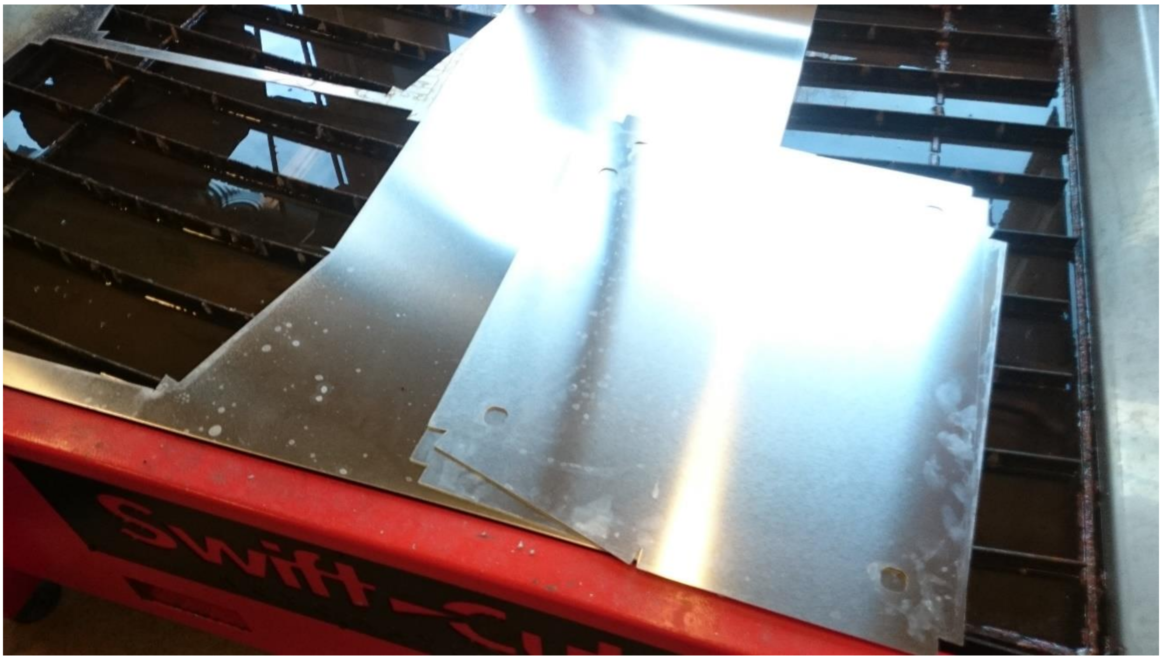


Figure 6-2. Lids for the electronic compartments after being plasma cut.

Figure 6-3. A photo of our helpful Rune Stensrud, teacher of production processes at Ås high school, here working with bending press forming machine, producing the lids of the electronic box...

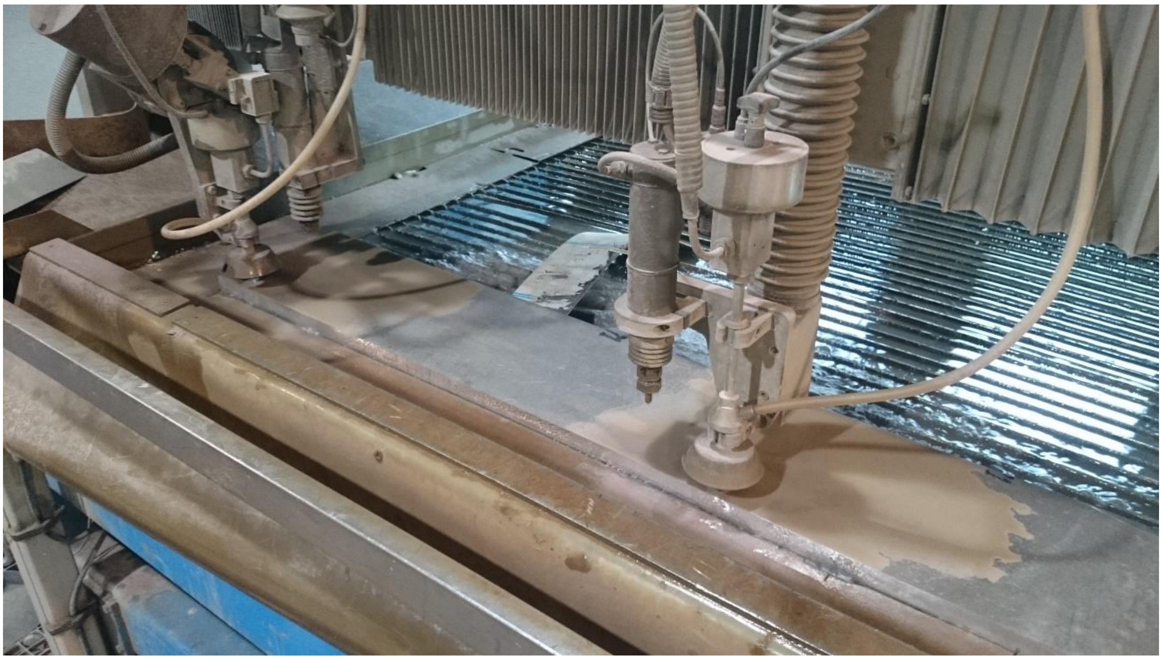


Figure 6-4. High pressure water cutting of aluminum suspension bridges, done by Dynatec SMV in Askim.

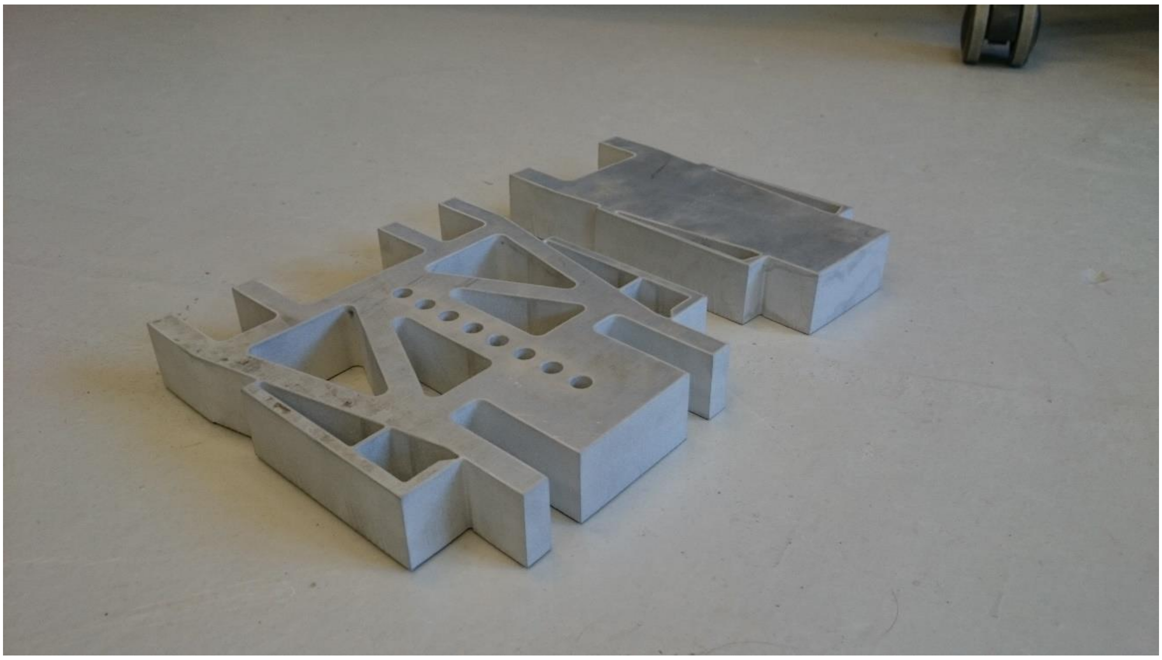


Figure 6-5. A picture of a set of suspension bridges taken straight out of the machine. For production purposes, I designed the suspension with supporting structure to make the further process of drilling hinge holes easier and more accurate. These supporting structures can later be cut away with a bandsaw.

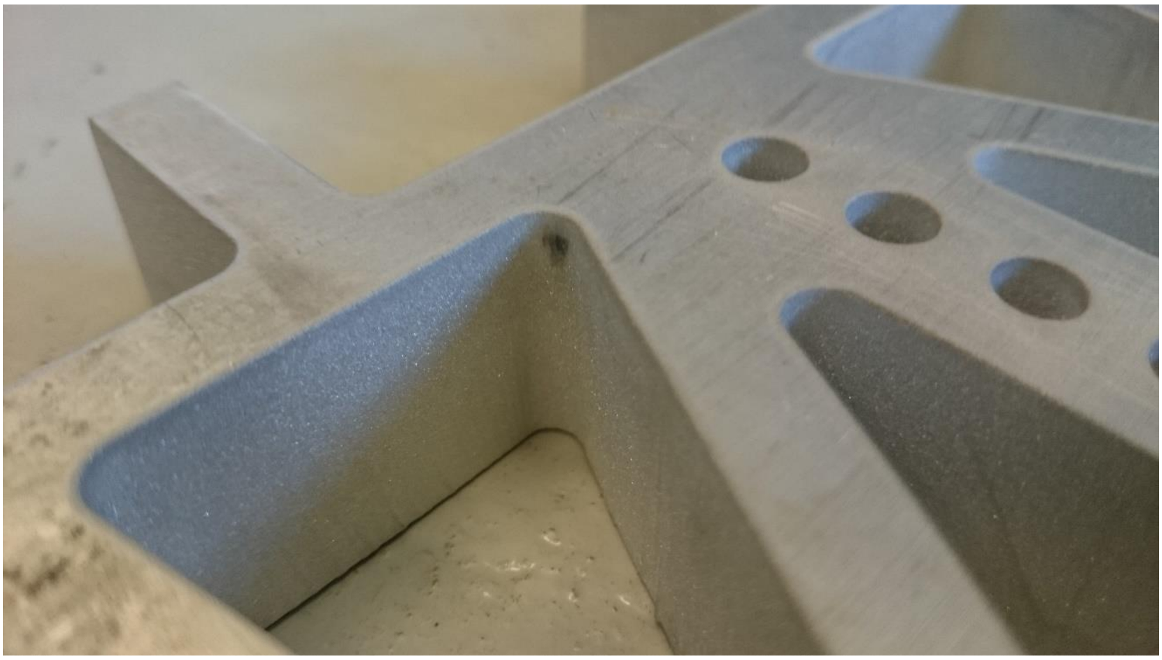


Figure 6-6. A close up photo of the lower suspension bridge showing the fine cutting details of the water cutting process.

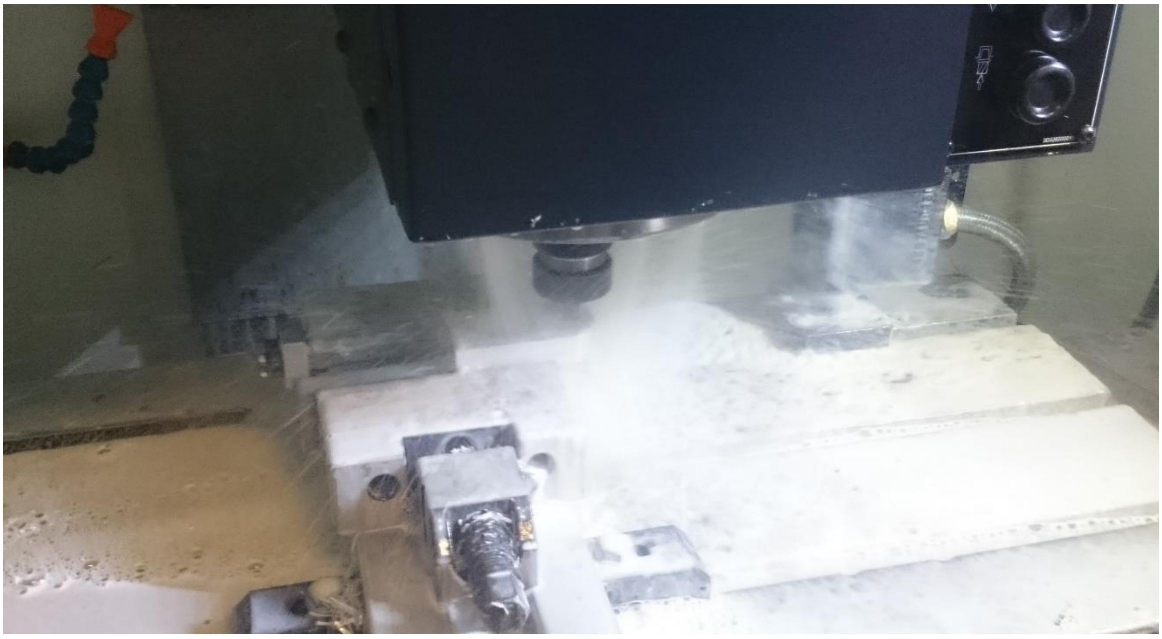


Figure 6-7. CNC- milling of the hinge tube clamps.

Figure 6-8. Hinge tube clamps nearly finished after CNC-milling.

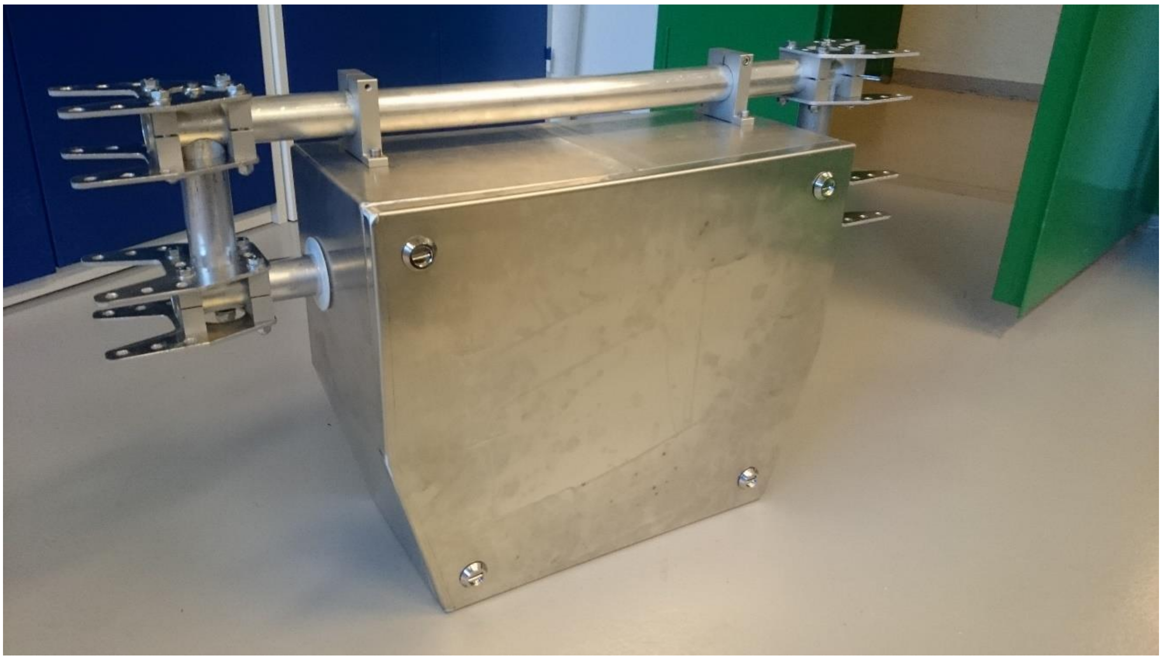


Figure 6-9. The nacelle core assembly containing the nacelle frame and the electronic compartment box.

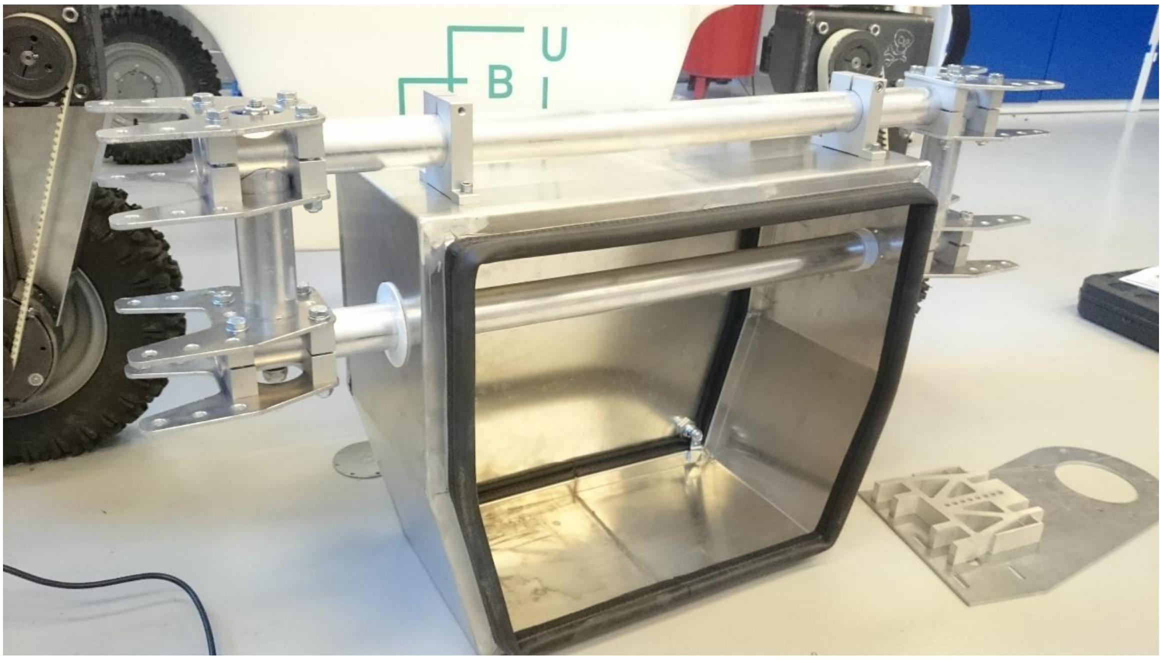


Figure 6-10. The Electronic compartmen internal view with rubber seal.

6.2. Costs

Frame and suspension material budget is set to 15000 NOK.

Table 6-1. Estimated frame and suspension costs per robot for standard configuration.

Specification	*Single Price [NOK]*	*Units/hours*	*Sum [NOK]*
NMBU Workshop hours	250	50	(12500)
Ås High School Workshop hours	0	200	(0)
Dynatec SMV hours	0	3	(0)
Glide bearings	20	64	1280
Cabinet locks	16	30	480
Dampers	1500	4	600
Profile technology	2500	-	3000
Materials	3000	-	3000
SUM			**13760 (26265 incl. hours)**

The sum of 13760 NOK is 1240 below the initially set material and component budget.

6.3. Experiences

The design process was a long process, even for a relatively simple idea. Since the requirement of increasing the Technology Readiness Level was very important aspect, I needed a lot of time and reflection of my design to make sure it is producible and robust, without compromising the flexibility. Good ideas rarely come by themselves in a dark cellar study environment for hours. Therefore, it is underrated to take some time off to relax the shoulders and do something completely else, suddenly ideas come by themselves. For example, many great ideas have come from drawing sketches in the sand on the beach while being on vacation. Therefore, I'm thankful for the trip to Brazil, as it was not all serious hard studying, and had a lot of fun as well.

When it comes to the building and production experience, there are still a few parts left to produce. The electronic box takes its shape and the suspension bridges look good. The most important pieces of the nacelle are mounted together, such as the frame T- connections and the electronic compartment.

The remaining work consists of finishing the suspension hinge tube clamps, drilling the suspension arms, lathing the hinge pins, and make the wheel assembly brackets. In addition, the glide bearings need to be pressed into the applicable parts.

Considering the remaining work, I am confident of finishing the robot in time for the Masters defense.

7. Conclusion of part one

7.1. Results and recommendations

I have managed to design a simple, rigid, lightweight and modular tube clamping frame concept. This concept is designed to be used with various tools up to about 200 kg, and its suspension is made to ensure contact of any wheel against the ground under normal conditions. Thanks to its modular concept, it is possible to reconfigure the robot into any possible kinds of configurations. By the feedbacks of my advisor, I have contributed the world of robotics, a concept that has not been seen before and hopefully has a promising future, if proven successful.

Since the robot has not been assembled yet, I cannot state at this point how well I have reached the goal of increasing the TRL-levels. The goal is to be able to demonstrate and prove the concept on my master thesis defense presentation.

The electronics case is designed to be waterproof enough to reduce the need of internal components protection against water. Due to the possibilities of condensation, or drops of water inside the cabinet, the design is made with a drain plate and drain holes on the bottom, to keep the components dry. The enclosure will not be able to have a higher IP-rating than the lowest rating of the belonging components, although extra sealant could increase waterproofing. Estimated rating of IP55 is applicable to the enclosure, described in section 8.

By feedback of the enclosure production, it is recommended with an increased material thickness of 2 mm to make it easier to weld. Riveting is also an option for applicable places.

Because of the restricted amount of time, I have only given a draft, and suggestion on how the “Thora” version could simply be designed by the use of purchasable components.

I have not managed to do calculations of every single situation because the limited time-frame, but the ones I have finished tell us that we have a relatively sturdy construction if the tubes only bend and create a X-directional deflection of about 2,4 mm with full possible propulsion of 1580 N at 200 kg payload. Recalling that these forces are calculated by the quasi static Vehicle Factor of two.

Because the frame is very flexible, experimenting is allowed to improve stiffness by adding tubes to the modular hinges in different configurations.

7.2. Future Work

Future work includes first of all building the model and finding the optimal configuration. This will happen during the following weeks. The plan is to do all we can within the master thesis defense presentation. This involves, getting all the parts needed to be finished. With my workshop experience, I am ready to assist to make sure to get the final pieces ready.

It is almost always expectable to find areas of improvement on the concept or design. Hopefully there is only minor changes that that are acceptable when making a product. The frame stiffness and sturdiness should be tested and validated to see if it needs any improvement.

Other works include building the Thora module, by purchasing standard steel roll cage hoops and weld it as a frame. This configuration of the concept does not require as heavy loads, as the main configuration, and should be designed accordingly.

A tool concept is to be developed further by the concepts I have suggested. It should to be able in the future to pick up tools autonomously, or by manual control. In this case, the suspension can also be further developed to be able to change the robots ride heights for convenient tool transport. The upper suspension bridge is designed without any light-holes to make it easier to design a vehicle leveling system later.

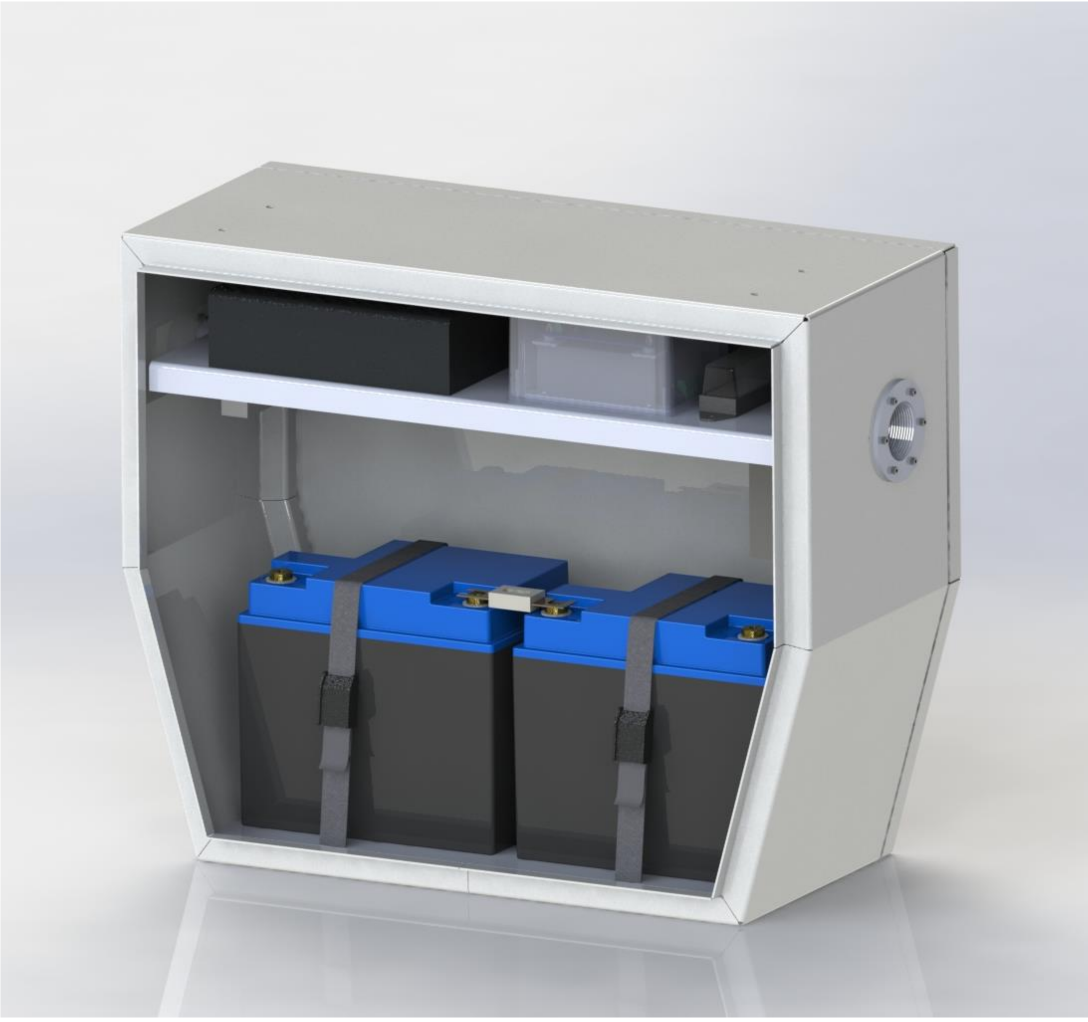
For improved design looks on the robot, a nacelle cover like in the renderings are to be made. Either in press formed aluminum, or even better, composite material.

Future improvements of the electric compartment by adding a double flange when Ås- high school upgrade their press forming tool.

When the concept is proven, further development can be done by making a concept of a quick battery change to improve the operational time.

Part 2

Electrical and Electronics Design



8. Grading and Classifications

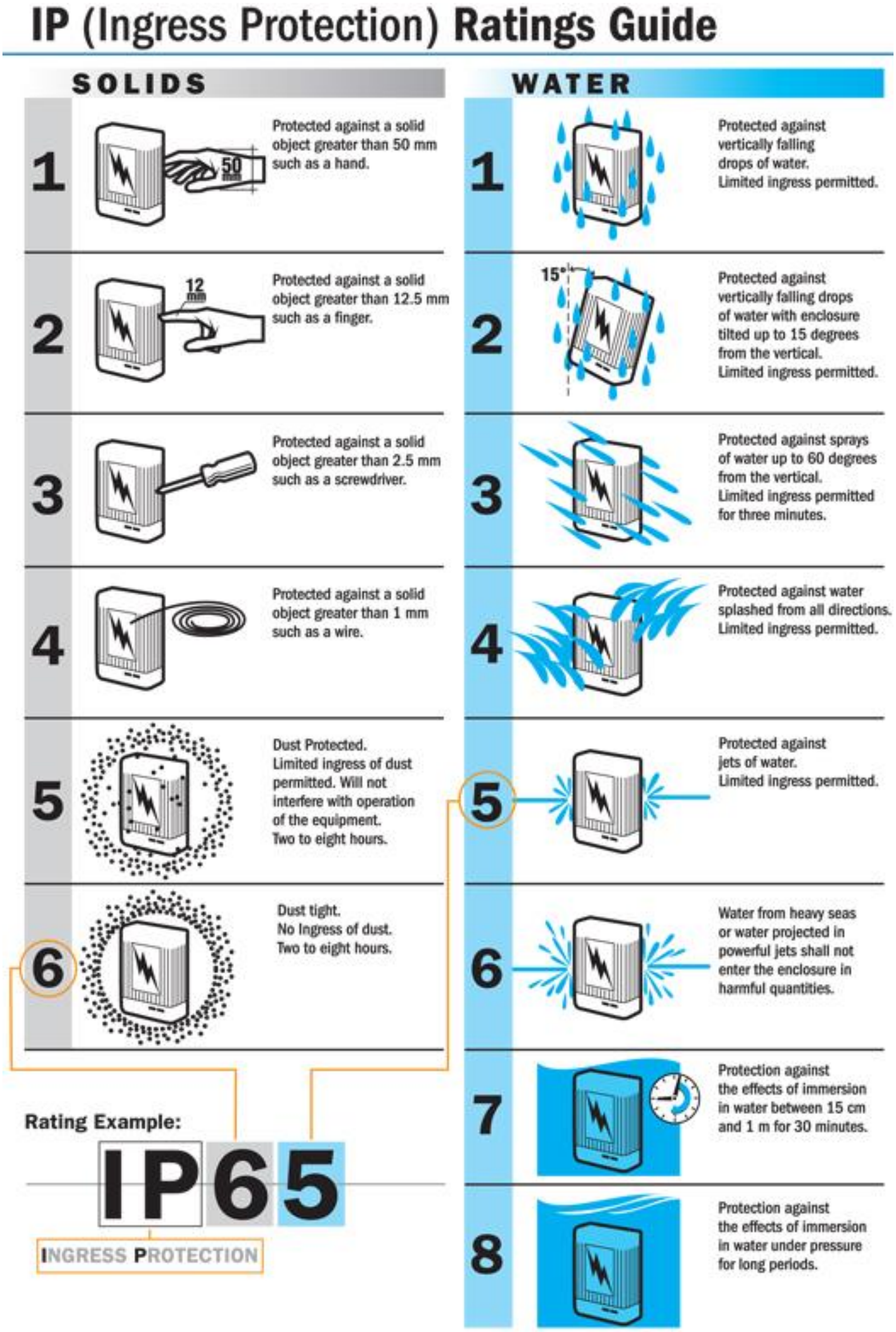
8.1. IP-Rating system

In order to protect electronics and the electrical equipment of the robotic platform from short-circuiting caused by the absence of water and dirt, it is necessary to protect vulnerable parts. The IP-grading standard ISO 20653:2013-02 describes how a commercial product are certified against different levels of dust and water exposure. Certified companies that receive a product before mass production, to undergo evaluation and testing, and implement these certifications based on results. The standard describes how to make water- and dustproof enclosures and the way of test execution. The standard is not available for everybody for free, as a copy of the standard is available for about 140 euros. The Figure 8-1 show us examples of how testing are conducted by TZO/LUW laboratory for a client.

Figure 8-1. These pictures show us examples on IP-grading tests conducted by the TZO/LUW laboratory in Germany. Picture to the left shows enclosures tested in a dust cabinet, while the picture to the right shows how the enclosures tested against high-pressure water jets [52].

The IP-classification rating levels describes by the IP-letters followed by two digits (IP-xx). The first set of letters describes how dustproof the enclosure is, while the second letter describes the waterproof ratings. In the Table 8-1 shows the Ingress Protection numbers explained.

Table 8-1. Explanation of the IP rating system, courtesy of Blue Sea Systems [39].



9. Electronics

9.1. Computers

In the recent years, computer technology has been shrinking, while simultaneously seeing an increase of processing powers according to an article in New York Times [53]. This opens up for a range of miniaturized computers with great characteristics, that do not take much space and have a lower power consumption than ever before. This means in the near future, that robotic systems do not need to carry a large heavy supercomputer onboard. Robots, especially humanoid robots, need to be swift and lightweight to be able to mimic the movements of a human without falling over and hypersensitive sensors need a lot of processing power. CPU processing powers is not all a modern robot needs. Today, we are also witnessing more autonomous and self-teaching algorithms for robotic systems, which demands powerful image processing. This relies on the need for cameras, sensors and laser scanners together with powerful GPUs.

I will be describing a few computers that could be suitable for Thorvald II, which will be using the ROS – Robotic Operating System, connected via a CAN bus chain network for the actuators. This robotic platform needs to be prepared for image processing in the way of recognizing different phenotypes for the planned anti-weeding processes.

9.1.1. SmallPC SC215ML iBrick

The iBrick is a small and powerful rugged computer with an Intel i5 processor [54]. Rugged means that the computer is put inside an all-weather compact enclosure protected against shock rain and more. The system is already in use on Thorvald I, and the cost is about 2000 USD for the same configurations.

Figure 9-1. The SmallPC iBrick 215ML featured with waterproof IP67 enclosure [55].

Table 9-1. Technical Specifications of the SmallPC iBrick SC215ML.

SmallPC iBrick SC215ML	*Specification*
Enclosure	Rugged/Waterproof IP67
CPU	4th gen i3 to 5th gen i7 processor
CPU Clock Ratio / Cores / Lithography	Up to 3.1GHz / 2 cores / 14nm
GPU	GPU not specified
GPU Operations	Not available
Ports	3 USB 3.0 ports
Storage	64GB SSD
Memory	Up to 16 GB RAM
Power Supply	6-32V DC input
Power Consumption	< 13W power consumption
Dimensions	207 x 129 x 69 mm
Price	2000 USD

9.1.2. Intel NUC i7

Intel has developed this small computer as a replacement for large desktop computers, without compromising performance in according to Intel [56]. This relatively cheap minicomputer promises powerful computing, but it might lack power in the graphic processing unit, for deep learning purposes.

Figure 9-2. The Intel NUC BOXNUC5I7RYH, here featured with a non-waterproof enclosure [57].

Table 9-2. Technical specification of the Intel NUC BOXNUC517RYH.

Intel NUC i7	***Details***
Enclosure	Standard
CPU	i7-5557U processor
CPU Clock Ratio / Cores / Architecture	3.1 GHz / 2 cores /14 nm
GPU	Intel Iris graphics 6100
GPU Operations	845 GigaFLOPs pr. second
Ports	4 USB 3.0 ports
Storage	Not included
Memory	Up to 16 GB RAM
Power Supply	19V DC input
Power Consumption	< 65W power consumption
Dimensions	115 x 111 x 49mm
Price	4995 NOK

9.1.3. NVidia Jetson TK1

Embedded platforms are computer systems, according to IoT Agenda [58], that are combined with a hardware and a software. It is often programmable, or capably fixed, so the system is designable for a particular function. The Jetson TK1 is one of these systems, and probably one of the most powerful one available today. This lightweight and small platform is perfect for UAV applications and robots that need computer aided vision and other compute-intensive capabilities [59].

Figure 9-3. Illustration of the small and lightweight NVidia Jetson TK1 Embedded Development Kit [59].

Table 9-3. Technical specifications of the NVidia Jetson TK1.

Details for NVidia TK1	Specification
Enclosure	Not included
CPU	NVIDIA 4-Plus-1™ Quad-Core ARM® Cortex™-A15 CPU
CPU Clock Ratio / Cores / Architecture	1,9 GHz / 4 cores / 28 nm
GPU	NVidia Kepler™ 192 CUDA cores
GPU Operations	300 GigaFLOPS pr. second
Ports	1 USB 3.0 port
Storage	Not included
Memory	Up to 16 GB RAM
Power Supply	5,5V to 19,5V DC input
Power Consumption	< 14W power consumption
Dimensions	127 x 157 x 40mm
Price	200 USD

9.1.4. NVidia Jetson TX1 Development Kit

According to NVidia [60], *the Jetson TX1 Developer Kit is a full featured development platform for visual computing designed to get you up and running fast.* This platform is Linux supported and features a low-power envelope for applications that need powerful computational performance. The computer is actually credit card sized, and comes with a developer board, that is flexible and easy to use for almost all hardware applications. With the GPUs 256 CUDA cores, that ensures high visual computing skills, the TX1 suits very well with autonomous systems and robotic vision.

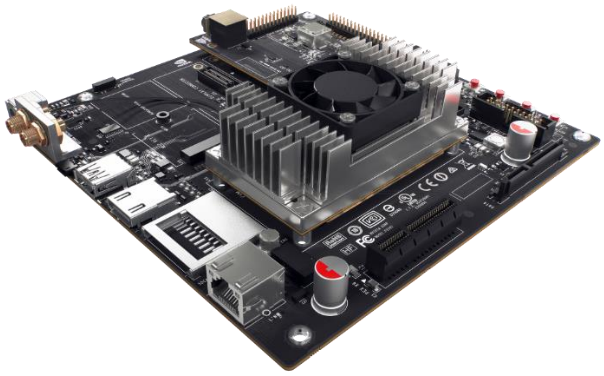


Figure 9-4. The NVidia Jetson TX1 Development kit. The computer itself is actually the credit card sized board below the massive heat sink, while the rest is an interface module for development purposes [60].

Table 9-4. Technical specification of the NVidia Jetson TX1.

NVidia Jetson TX1 Features	**Specification**
Enclosure	Not included
CPU	Quad-Core ARM® Cortex™-A57 MPCore
CPU Base freq.	N/A
Number of CPU cores	N/A
Lithography	20 nm
GPU	NVidia Maxwell™ architecture 256 CUDA cores
GPU Operations	1 TeraFLOPs pr. second
Ports	1 USB 3.0 ports
Storage	Not included
Memory	Up to 16GB RAM
Power Supply	5,5V to 19V DC input
Power Consumption	< 10W power consumption
Dimensions	170 x 170 x 50 mm
Price	599 USD or 299USD with educational discount.

9.2. Computer Interface

9.2.1. Input devices

The traditional way for computer input is to use auxiliary devices like keyboards and a computer mouse. Today we have screens with touch capabilities, well as voice inputs and on-screen keyboards. These features supersede the keyboard and mouse input devices, but programmers still hold on to traditional method. There are many reasons for this, such as it is still a way faster and more exact input method. With a traditional keyboard, you get a feedback when pressing the keys, and you can also feel the distinction between the keys, and a mouse is more sensitive than the large tip of a finger. Thorvald is a robotic platform with the possibility of connecting any input device via an USB-port, so there is no reason for having a keyboard fixed onboard. Most of the programming work is done in a workshop or a laboratory, but it would be nice to have the possibility to do small changes in the field. If there is just a normal screen onboard without touch interface, Thorvald could benefit from having a waterproof trackpad.

Figure 9-5. A waterproof IP68 Track Pad by the NSI Keyboard and trackpad company [61].

Other input devices that is helpful for Thorvald, is a Joystick. This is because the robotic platform is in the next few stages of development not yet autonomous. A joystick makes it easier for manual control of the robot, and is more than enough to do testing, demonstrations and so on. A cheap and simple way is by connecting a wireless gaming console joystick by Bluetooth. The Xbox One controller shown in Figure 9-6 is already successfully implemented on the Thorvald I platform.

Figure 9-6. The Xbox One Controller is often used as a input device by connecting to a normal computer [62].

Robotic vision helps the robot identifying objects or people, and can be done by the use of ROS integrated with OpenNI [63]. This allows using an Xbox Kinect stereo camera to the computer while doing image processing shown in Figure 9-7. Figure 9-8 shows a stereo camera for robotic purposes in a IP65/67 embodiment.

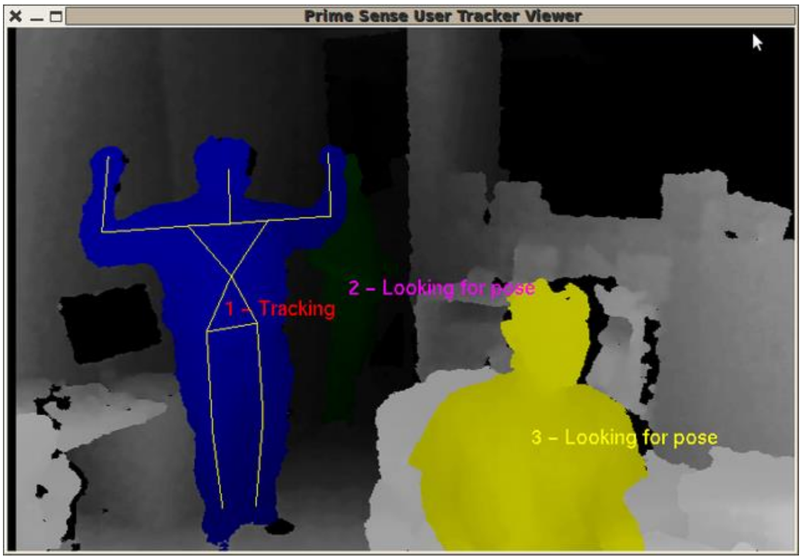


Figure 9-7. Recognizing, tracking and dividing between human beings and surrounding non-interesting object [63].

Figure 9-8. A 3D vision IP65/67 stereo camera made for robotic purposes [64].

9.2.2. Output devices

Screens are used as an output device from a computer so that humans can easily interact. Traditionally computer screens have no input, but it is now common on every type of electronic devices. Thorvald would benefit from a screen, as an easy way to make changes or start a specific program. A few important features needs taking into account when making a decision. As the robot is moving around outdoors on a sunny day, screen brightness would be very helpful to avoid a low visible screen. Second, the screen is exposed and not protected by a weatherproof box, so the need of a rugged system is not a bad idea. The screens in Figure 9-9 and Figure 9-10 shows examples of waterproof screens.

Figure 9-9. The SD100PM. A high brightness IP65 panel mount screen, used on the prototype. Only the front bezel is waterproof and is not waterproof if put on a non-waterproof panel or box [65].

Figure 9-10. The SunVU RWD085M. A high brightness IP65 freestanding, clamp-able screen. An idea is to clamp this screen to the tube frame. Easy to take off when job is done [66].

It would be an exciting feature to give Thorvald a voice. Artificial voice generators can be installed on the computer system. Allowing Thorvald to give simple voice feedbacks or telling people to move out of the way. Figure 9-11 shows an example of a waterproof speaker.

Figure 9-11. IP65 Speaker enabling robot voice [67].

9.3. System Communications and Software

To get the robotic platform up and running, a few important following requirements of software and communications protocol implementation for the computer are set.

9.3.1. Controller Area Network – (CAN bus)

Every operating component on the platform needs to be linked together in able to communicate. One form of communications protocol is the Controller Area Network (CAN bus) developed by Robert Bosch for the car industry in the 80s to reduce the number of harnesses and complexity. The principal is that instead of sending signals through a wire to each individual component, every signal is routed through all systems like a daisy-chain. This chain sends a pack of data containing 11-bit, or 21-bit of information to every system component called nodes, but with a particular address for a particular node. This particular component reads all data, and only sorts out the information with its own address while passing on other messages. Bit rates are typically 500 -1000 kbit/s. This data protocol is perfect for small amounts of data, delivered quickly and reliably.

9.3.2. CANopen

The CANopen communication, developed by CiA, is a multiplatform, open source communication protocol which is based on the same principles as the CAN bus protocol [68]. It is used for embedded systems for the use in automation. This protocol sends 16-bit index plus 8-bit sub-index arrays of variables. If non-automotive, or industrial computers are used, this communications protocol can be used for a wide amounts of computers.

9.3.3. Robotics Operating System – (ROS)

The ROS, Robotic Operating system, was built to promote robotic collaborations, and include a number of software frameworks for robot development [69]. The program tools are language-independent and include open source libraries for Python, C++ and LISP, which makes it available for free for both commercial and research use.

9.3.4. Ethernet

Some sensors generate a large amount of data, to be able to communicate or send data to the computer, Ethernet is a widely used communications protocol for moving large data between systems. Communication between systems confined in a local area is called LAN (Local Area Networks), while communication to other far non-local nodes are called WAN (Wide Area Networks). These communications are done by a standardized RJ45 plugs and sockets, and are used by most of the computers today [70]. Classical Ethernet protocols and network topology may not be optimal for deterministic time-and safety-critical applications, and therefore special real-time variants have been developed including TTEthernet (Time Triggered Ethernet developed by TTTech Computertechnik AG) used in modern high-end aircraft avionics

9.3.5. Universal Serial Bus – USB

A lot of sensors and other equipment is also using Universal Serial Bus (USB) communication protocol. USB has been on the market since 1997, and has been several times, mainly for increased communications speeds. USB 2.0 and USB 3.0 are both used today, as the latest version is still relatively new. Both USB 2.0 and 3.0 systems are compatible and will fit, but since the USB 3.0 has five extra pins, it is only possible to get the speeds of the lowest combined system. This means, when two USB 3.0 systems are connected with an USB 2.0 cable, the systems can only communicate in the speeds of the USB 2.0. To get maximum out of the communication speeds, it is important for the computer to be compatible with USB 3.0. Figure 9-12 shows how USB 3.0 can achieve higher speed and still be compatible with USB 2.0 systems.

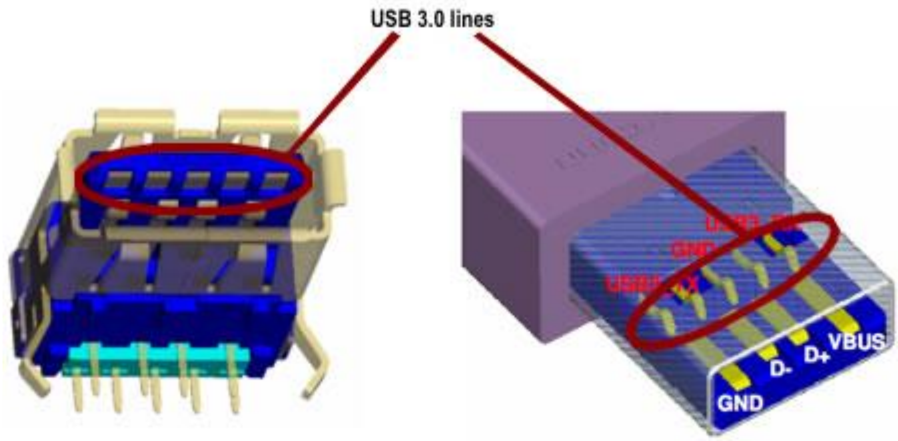


Figure 9-12. This image shows how USB 3.0 can achieve higher speed and still be compatible with USB 2.0 systems [71].

9.4. Batteries, Power Up and Safety Systems

To be able to safely turn on or off the robot without destroying the system and compromising safety, it needs a system that control the power source and automatically sequence the initial power up procedure. This system is also responsible for keeping the system up and running or stopping the robot when an emergency button is pushed. Other examples include finishing a manual or automotive duty, were the computer or system sends a power down signal to safely perform a shutdown sequence. These systems can be made by microcontrollers or programmable modules, by controlling relays.

9.4.1. Batteries

Batteries are an essential power source for any electric vehicle. Batteries consists of multiple galvanic cells to create the required voltage. When charging or discharging a battery, these cell gets uneven voltages. These differences are smoothened out by using a Battery Management System (BMS), that basically leaks excess power from one cell to the deficit cells. Based on the Thorvald I prototype battery selections and experience, the original BMS in the original Golden motor battery in Figure 9-13 was just not good enough, and was replaced in the original project. The new design needs a battery with a high-grade BMS that can communicate with the computer system to get maximal amount of power out of a battery cycle.

Figure 9-13. The Chinese manufacturer, Golden Motors LFP-4830M LiFePO4 battery, used on the original prototype [72].

After studying different kinds of standalone high-grade BMS for the original battery, we contacted a supplier of batteries, Gylling Tech AS, for experts advise. After a visit by Gylling's salesperson Kenneth Hilton [73] the NEC Li-Ion ALM12V35 shown in Figure 9-14, was recommended for our project which communicates via CAN bus, suitable for our system.

Figure 9-14. The NEC ALM12V35 Li-Ion battery with BMS communication by CAN bus, strongly recommended for our application by Gylling Tech AS [74].

9.4.2. I/O Modules

Programmable I/O modules, where “I” stands for “in” signals, and “O” stands for “out” signals, controls signal and power based on a desired program designed by the user. This ensures the module to switch signals to a desires relay, which power on certain systems.

SYSTEC electronics delivers such system, and a benefit for this manufacturer type of modules is that these can communicate via CAN open protocol, making it easy to switch signals while the robot is operating.

Figure 9-15. This I/O module from SysTec is capable of communicating via CANopen protocol, and is capable to switch via 16 ports[75].

Benefits of these modules include sending emergency signals if module should fail. It communicates via CANopen and is able to monitor onboard temperatures and power supply. Signals should usually be powerful enough operate simple components like relays and so on. However, it is expensive and it demands a 24 V power supply which means another voltage converter when system operates in 48V, 12V and 5V. Temperature and power supply monitoring is also possible to do via onboard computer or combined microcontroller.

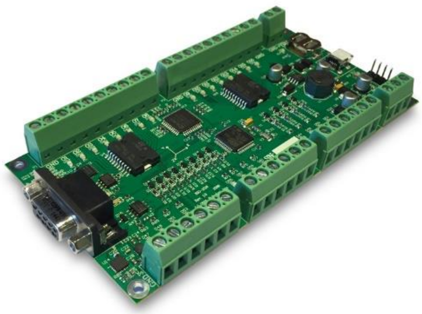


Figure 9-16. The RIOX-1216AH I/O extension module from RoboteQ, providing twelve inputs, and 16 outputs. This is the same manufacturer that provide the motor controllers for the wheel modules [76].

9.4.3. Programmable Logic Controller - PLC

PLCs are basically a programmable digital computer that is used for switching industrial electromechanical processes based on both inputs an output much like the I/O module, but are often mora advanced and has more features. Normally, PLCs also has more calculating powers. These systems are usually quite robust and uses backup batteries in case of source power failure. The main feature of both the I/O module and the PLC, is that these works as a standalone controller that don't need any additional electronic circuits or components to work.

Figure 9-17. Image shows an example of a programmable logic controller by DirectLOGIC [77].

9.4.4. Microcontroller

A microcontroller is a simple small programmable chip that is able to switch and monitor via inputs or outputs. It is very cheap and often uses well-known programming language like *C programming.* Other computer based microcontrollers can also use the *Python programming* language. The most common microcontroller today is probably the *Arduino.* This Italian manufacturer has sold over 700.000 official microcontrollers, both for hobbyists and professionals, and since this is an open-source product, there is estimated a same amount sold in copies. Figure 9-18 shows different versions of Arduinos, ranging from large to small modules, often for different applications.

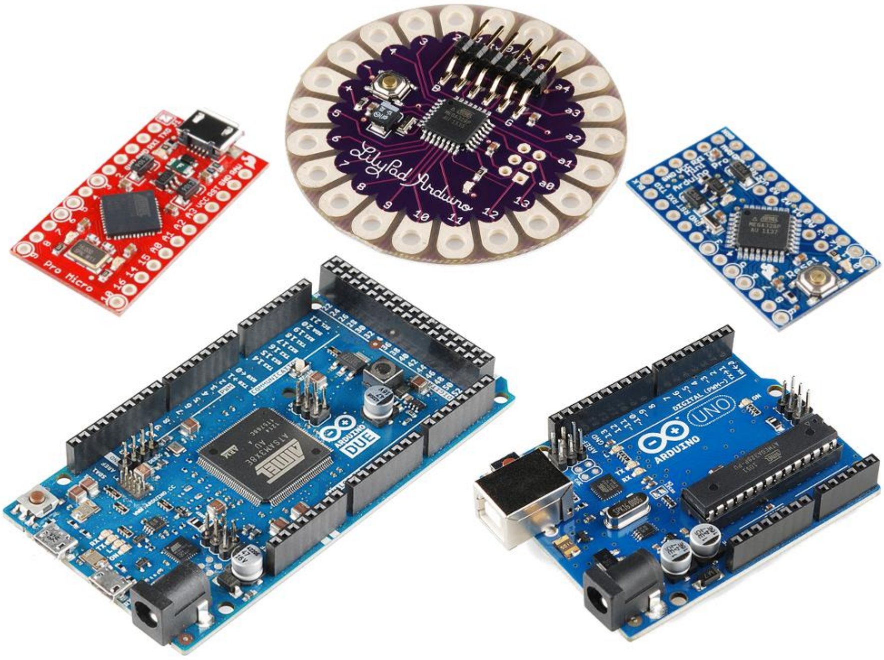


Figure 9-18. Different versions of Arduinos from small to large [78].

One of the great benefits of Arduino is the enormous communities online. Whatever you want to create, someone has probably done is before you and is available online. The downsides are however the lack of CAN communication. This is however possible to control via the CANopen operational onboard computer with I2C-protocol. Arduinos has relatively low signal power which mean that the usually can't do operations on its own. It is necessary with transistors to create the required power of a relay.

9.5. Electronic Components and Methods

If going for a microcontroller it demands a bit if extra work. Its lack of signal power, requires transistors and resistors to control relays or other power consuming components.

9.5.1. Power Converter

To supply components with the correct DC voltage, different from its system DC voltage, a DCDC converter is needed. These converters ramp up or down the system voltage to the required level. The choice of a power converter is based on the components required voltage, power consumption and the desired efficiency of the system. Different converting technologies has different efficiencies and costs. Figure 9-19 shows the linear converter model used on the Thorvald I prototype, it is a relatively cheap model, but has a low efficiency of 78%.

Figure 9-19. The low cost MEAN WELL SD-50C-12 used on the prototype to supply the onboard computer and screen [79].

These converters produce 22% of the power conversion into heat that has to dissipate through the holes in the casing, making it harder to protect in a box without overheating, particularly at high ambient temperatures. To find a more efficient power converter that produces less heat we need to look for “buck” down converters that has a typical efficiency of above 90%.

9.5.2. Soldering

Soldering is a method of binding electrical components to an electrical circuit board and creating a good reliable conductive connection between other components and the board. The typical binding medium for electronic devices consists of a low molting temperature metal alloy containing typical 60/40 relation of tin and lead. The melting point is about 183°C for 60/40 tin/lead alloys, and 250°C for lead free solder. Lead free solders are approved by the RoHS directive (Restriction of Hazardous Substances Directive) that are working for environmental regulations in the electronic industry. Unfortunately, these lead free solders require a higher solder temperature and makes it harder to solder heat sensitive components like transistors and diodes which can easily be damaged, in the same time it’s harder to create a reliable joint. It is recommended that systems in the need of extreme reliability should be soldered with lead containing solders. These components, and all other electronic components should be carefully discarded at adapted recycling center.

9.5.3. Breadboards and Stripboards

To get a permanent, safe, neat and tidy connection between electronic components, it is necessary to organize them on a board. For prototyping and design testing, it is normal to use a breadboard with pin friction connection to easy install and remove components and wires. The next stage is to solder the tested and working circuit on a standard copper stripboard, which need adaption in form of copper traces. This is normally done by using a knife or a Dremel-tool to cut off copper traces to match the circuit. By soldering wires, it is possible create a bridge between traces. All in all, this is a lot of work for one circuit, especially when making complicated circuits, or making multiple copies. It’s also hard to connect a whole circuit board without doing errors the first times as it is easy to loose overview.

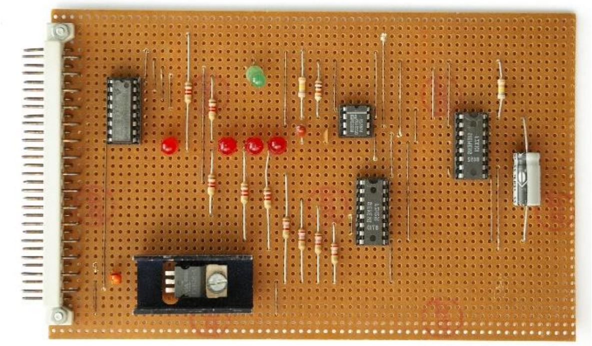


Figure 9-20. Example use of stripboards with solderable copper strips on the back [80].

9.5.4. Printed Circuit Board – PCB

Printed circuit boards are safe, reliable and easy to install with components. Using certain programs, it is possible to draw a circuit with a good overview, then convert the circuit to a PCB. This demands a bit of design job to make it done correctly, but when making multiple copies, it saves you a lot of time. When design is done, it is ready to get produced by an external manufacturer. When produced and ready, every traces are exactly the way you need them, this allows components to be soldered on, hopefully, without any major changes. PCBs are essential if the goal is to make a finished product, as it meets the costumer’s expectations when it visually looks like a complete product. The downside is that PCBs generally get more expensive with fewer copies, so the more the merrier.

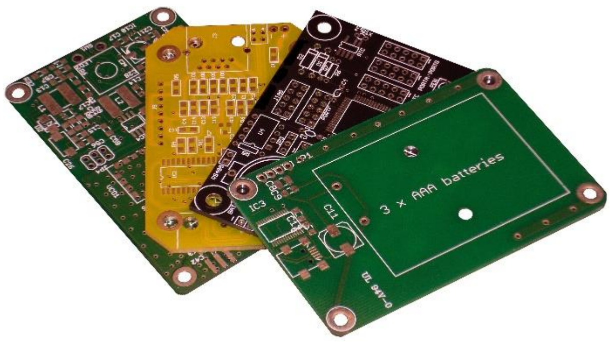


Figure 9-21. Examples of custom printed circuit boards [81].

9.5.5. Relays

Electromechanical relays are electronic switches, using a coiled electromagnet. Its delivered with different power characteristics, for high power switching and low power switching. Switching is controlled with an electric current, directly from a I/O module, or via a transistor when using a microcontroller. Powerful relays can be used to apply the main power to the system. These power relays, called contactors, also demand a larger current to operate, and are usually powered by a smaller relay. The importance of relays is to route power where, and when it is needed. Relays offer a good galvanic separation for systems with a multiple power system, which ensure no current leaks between these systems. Relays are also an essential safety feature, as relays often are either normally open (NO), or normally closed (NC). Normally open relays ensure that when relay power is lost, due to system failure or emergency button is pushed, the relays switches to its normally open position, cutting all battery power and stops the robot.

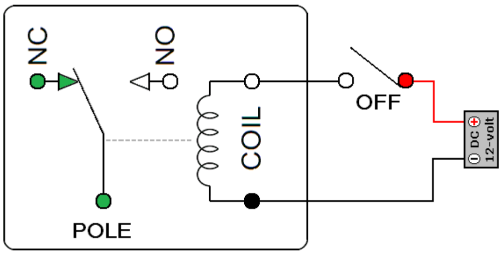


Figure 9-22. A relay often has both normally open and normally closed ports to choose either, or use a combination [82].

Other types of relays include SSR (Solid State Relay). These relays have no electromechanical, physical moving parts that causes relays to wear out. It consists of a high current semiconductor, much like a transistor, but capable of a much higher power. Solid state relays are reliable and safe, capable of a higher number of switching operations than the electromechanical relay. The major downside of these relays are the costs. SSRs for high DC switching currents are hard to get, and expensive.

9.5.6. Transistors

If a microchip signal is not powerful enough for the desired operation, it is common to use transistors to amplify, or switch these signals. A transistor may be either of MOSFET, FET or bipolar types, the former two commonly used when high-speed, rail-to-rail performance is important. The classical bipolar transistor is rugged and suitable for our applications and consists of a semiconductor material, with three terminals that are required for operation. The base pin (B) is for signal in, the collector (C) is wired to the power source, and the emitter (E) emits power when base signal is high for NPN transistors or low for PNP transistors. For switching purposes, either the collector or emitter is wired via the desired components. By using a NPN transistor, it can be used as a switch to supply power to the component when the signal is high, which is the usual configuration.

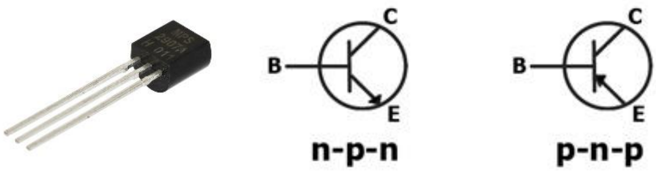


Figure 9-23. A transistor and its symbols for NPN and PNP configuration [83] [84].

9.5.7. Resistors

Some components have a low internal resistance, this could cause the component to get destroyed, or in worst case start burning. Other component require a certain voltage input or current to work properly. To reduce and adapt the power, it is necessary to install a resistor prior to the component. Using Ohm law (9.18), it is easy to calculate the necessary resistance needed for the individual components.

$$U = R \cdot I \tag{9.18}$$

9.5.8. Diodes

Diodes are often described as a one-way street. The electrical current can only flow in one direction. These components use semiconductor technology to allow a flow from the anode to the cathode nodes of the component shown in Figure 9-24. In this thesis, diodes are an important component used together with a relay as a “freewheeling diode” shown in Figure 9-25. This means that the coil produces a voltage spike when the relay power is shut, to get rid of this energy, the diode makes sure to make a path for the current back in to the coil, avoiding damaging other nearby component.

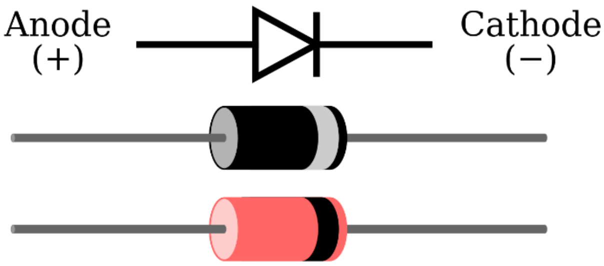


Figure 9-24. This illustrates the symbol and the looks of a typical diode. The current can only pass from the positive anode to the negative cathode [85].

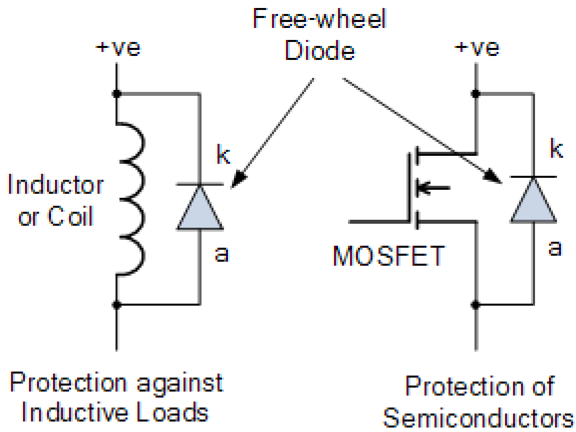


Figure 9-25. Uses of a freewheeling or flyback diode for relay and semiconductor purposes [86].

9.5.9. Terminals

There are a number of terminal types that can be used to supply the PCBs with power, and connect communication and signals to rest of the system. These terminals vary from common pinned terminals, to screw terminals. Pinned terminals require tools to shrink a pin onto wires, these pins are then snapped into plastic casings. The pinned terminals are usually for permanent systems. It is reliable but requires a bit of work. Screw connectors and cable shoes are perfect for a modular, flexible solution. It is easy to change connections, experiment and retrofit.

Figure 9-26. From left to right: high power screw terminal block [87], low power screw terminal [88], Molex pin contact [89].

9.6. Connectors

Sensors, input devices and output devices need to be connected to the onboard computer. This computer should be protected against water in a waterproof box or compartment, to avoid failure or short circuits. Therefore, it is important to ensure waterproof connections via HDMI, USB and Ethernet. By using the proper IP-rated connectors that both protect the signal cable and the internal component against water, we can get an improved system reliability.

9.7. Wiring

Wiring between system components are depended on the power consumption of the individual components. By knowing power consumption of the components and voltage, we can calculate currents needed. Current and wire lengths are considered when finding a suitable wire thickness. Wire thicknesses are measured in either AWG (American Wire

Gauge), or square millimeters. By using available lookup-tables, or charts it is easy to compare length, cross sections and amount of power for a wire. Instead of a large number of different wire sizes, it is easier and cheaper to use the same sizes for groups divided into High power, medium power and slow power signals or similar.

9.8. Fuses

Fuses is an essential safety feature. If a system failure causes short circuits, the amount of current causes the fuse to brake, stopping further temperature rise. Fuses can also restrict certain components power consumption. Although fuses react on current, and not voltage, it is important to follow the right voltage specifications for fuses. Neglecting these ratings, can cause a continuous arc to occur between the broken surfaces, making the fuse useless.

9.8.1. Battery Main Fuses

By bolting a fuse directly to the battery pole, it reduces the risk of a short circuit between the battery pole and the fuse. These fuses are normally of a higher current restriction than the rest of the system, since batteries often endures high currents for a short time without taking damage.

9.8.2. System Fuses

System fuses are used to break when a component has an excessive power consumption or a short circuit happens due component failure or other conditions. These fuses are primarily to reduce damage to surrounding vulnerable components or itself, and has a lower current restriction than main fuses.

9.9. Electrical Static Discharge - ESD Protection

All component including computers and small electrical components are sensitive to Electrical Static Discharge (ESD). Electrical discharge occurs by contact, friction and separation of materials and is a product by the difference of electrons between to materials [23]. I small noticeable static discharge for human beings are about 3000 V [90]. These high voltage discharges can damage sensitive electronics, particularly MOSFET or FET devices. If a symbol shown in Figure 9-27 is present on a component, show extreme cautions on handling the product by the use of approved antistatic wrist bands and approved ESD protective tables and equipment.

Figure 9-27. If a symbol like this is present on electronic components, show extreme caution to not destroy the object [90].

10. Requirements

The electrical systems need protection from water for a certain degree as the first version of Thorvald only had a waterproof computer and screen. This means looking into other products and its solutions, while considering the best choice for the design. By looking into certifications on waterproofing, I can consider which degree of waterproofing that is suitable for the system even if certification is not an option for this master and prototype.

Other demands mean finding suitable components that might be cheaper, or better than the last version. The electronic arrangement needs to be nice and tidy in a way that makes it easy to change components as well as troubleshooting the system. The choice of batteries will not be a part of my master thesis as it turned out to be quite comprehensive, and is a covered by a separate thesis.

11. Process of Design

11.1. Component Selection

Computers

The choice of different components is based on discussions and needs for the project. It has to be a relatively powerful computer with the possibility of high performance image processing. Image processing requires a powerful Graphics Process Unit (GPU).

All computers have the possibilities of installing a Linux based Operating system, ROS and OpenCAN. They also have the possibilities of using Ethernet and USB 3.0.

A safe choice would be the SmallPC iBrick, as we know it works from the prototype, but it is extremely expensive. The IP67 IP-rating on the iBrick is probably what makes it costly, and is not necessary for a protective electronics compartment.

The Intel NUC is probably what comes closest to the iBrick in processing power, both has a powerful Computing Processing Units (CPU), and GPU's are probably in the mid-high range. The NUC does not have any protective casing, so it needs extra protection. Since the NUC and other platforms has standard formats, it is possible to get hold of casings of a higher IP-rating.

NVidia Jetson TK1 is the little brother of the Jetson TX1, this computer has a high graphics processing power compared to size and its low price. This unit is designed for small flying robots like UAVs, micro-copters or popularly named "drones" with augmented robot vision. The computing skills are relatively powerful, but is below what we had in mind.

A brand new addition to the world of robotics is the NVidia TX1 developer board. Its credit card size computer is able to process powerful graphics tasks and is especially designed for robotic vision and image processing. This seems to be perfect for the phenotyping imaging projects at the Vollebekk research farm in Ås. It is also good for later robotic vision development. Even if the CPU power could seem a tad low, a powerful GPU is more important for robotic processes.

The Jetson TX1 is our first choice of computer, second the Intel NUC if the first choice should not meet our expectations.

Batteries and Power up system

After some discussion, we wanted to go for the costly NEC ALM12V35 batteries that has excellent BMS-monitoring system for our system. Other alternatives included same batteries as on the original prototype with an external professional BMS systems. These systems proved to be quite expensive, in addition, we did not know if these systems would works as expected with the batteries.

To power up the system, I have chosen to upgrade the initial startup circuit by using PCB, microcontroller, custom printed circuit boards and relays. The background of this decision is several factors. My team and myself are familiar with the use of Arduino and C-programming language. Relays provide high galvanic isolation if the system should later be upgraded with a separate battery system. This isolates electrical systems apart to prevent current flows and other disturbances. The chosen relays are of a good, robust and sealed type for the automotive industry. It has a high current flow rating compared to other non-mechanical systems.

If I am successful in making a custom PCB design it should be fairly easy, quick and cheap to make multiple copies of the board.

Other Components

Fuses in addition to current and voltage ratings, fuse response time (fast or slow action) must be compatible with the intended application.

Wire Thickness voltage drop considering wire gauge, wire length and maximum current as well as heating due to ohmic losses need to be considered.

The main contactor relay will be similar to the Thorvald I prototype, which had good results.

11.2. PCB Design Process

The design of the electronic overview is based on the first prototype of the Thorvald project. There is however both major and minor design changes in both the electrical systems and electronics.

By following the requirements on startup sequence and hardware. The design could be started. By using the program Scheme-it from Digi-Key [91] I could easily make good looking electrical sketches. The Figure 11-1 shows the final sketch up of the electrical system, and the electronic systems in the pink and green boxes. The pink boxes represent the electronics and power converter for the wheel modules, and is a separate master thesis by Marius Austad. The green box represents the custom microcontroller I/O power up system shown in Figure 11-2.

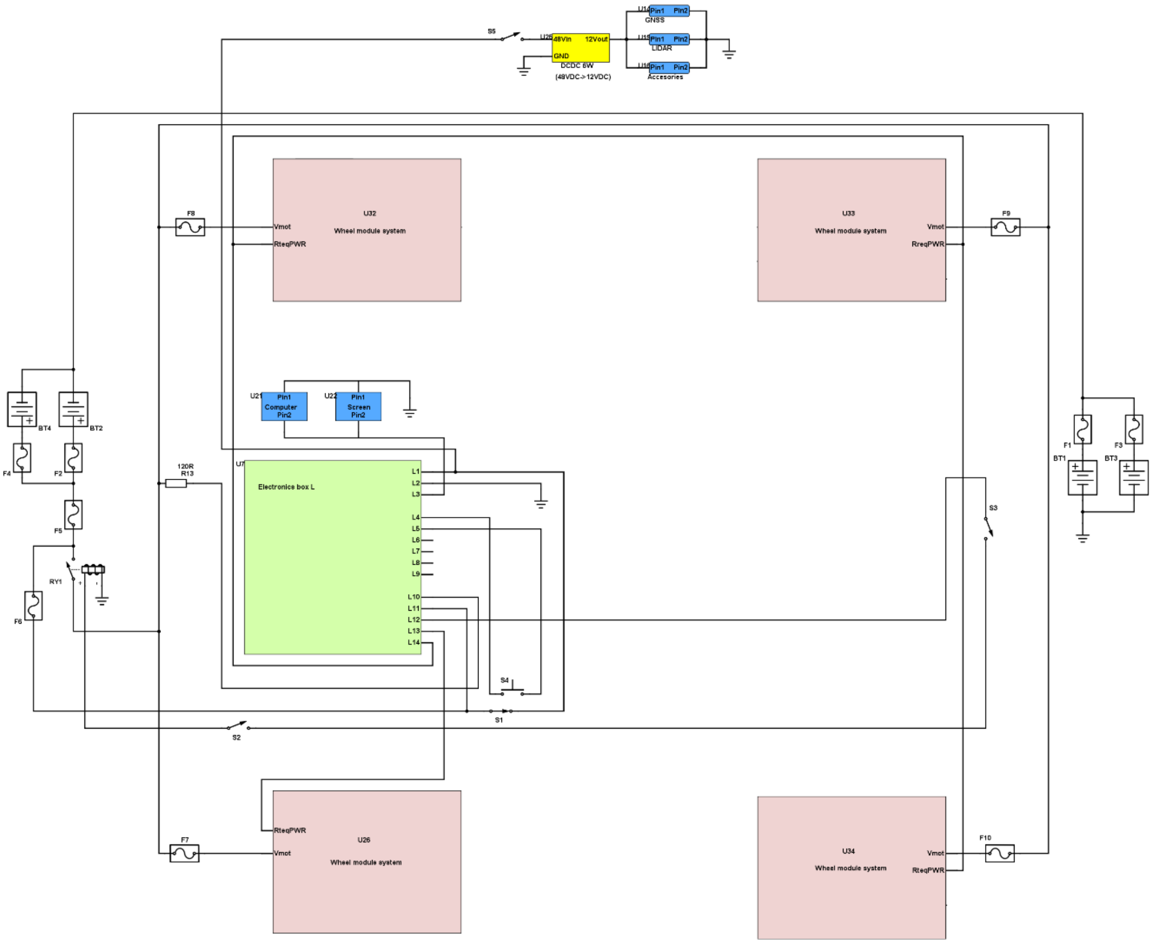


Figure 11-1. Electrical and electronical overview. This schematic is available as a large format an appendix.

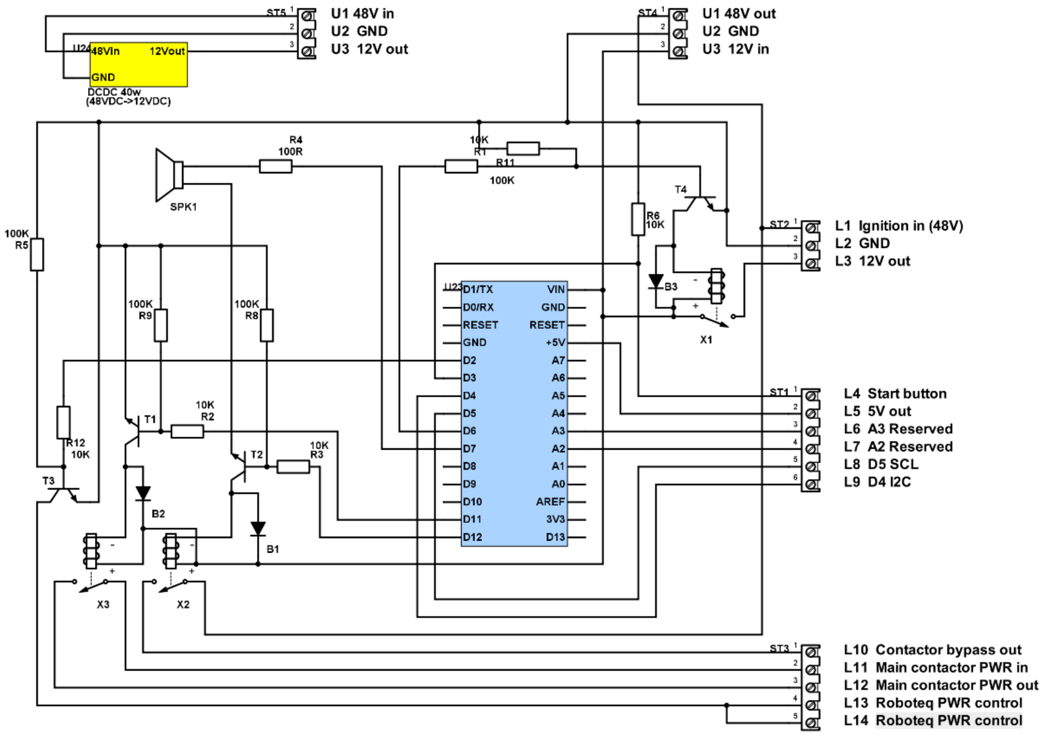


Figure 11-2. Electronical overview of the microcontroller I/O board.

The custom I/O board shown in Figure 11-2 is made by the combination of an Arduino microcontroller, transistors and relays. Necessary components are also embedded on the board. The startup sequence follows:

1. The S1 Ignition key supplies 18 V power to the 12 V DC-supply which delivers 12V to the Arduino.
2. If the S5 switch is in closed position, the sensor rack in the front center of the robot get power and turns on.
3. When the S3 button is pushed, Arduino turns on.
4. The computer and screen starts up by the Arduino signal closing the X1 relay.
5. The Arduino is programmed to supply power to the X2 relay which closes the circuit and delivers power to the wheel module motor-controllers through the R13 bypass-resistor.
6. The Arduino sends a signal to the T3 transistor that connects the motor controller power control to chassis earth, (battery negative node) like a car.
7. The capacitors in the motor controller get slowly charged up to avoid arcing in the system.
8. After a timeout, the RY-contactor relay closes by sending a signal to the X3 relay, and the X2 relay opens. Continuously serving power to the motor controllers.
9. The robot and its motor controller is ready to take commands from the computer.

10. Whenever the power is cut by the S2 or S3 Emergency Power Button, the main relay RY1, will lose its power and open, instantly cutting the power to the motor controllers.

Sensor rack and computer can be turned on individually for lab testing. This could be done by programming a pushing sequence for the S3 button. Other ports on the I/O board are not in normal use, but are reserved for other purposes like for example connecting the computer to the Arduino enabling computer control of the board.
To produce this board I have chosen to make this as a custom printed circuit board (PCB). This makes it easy to produce multiple copies only by the use of manual or wave soldering without a lot of wiring work. To produce these PCB-cards I have been using Autodesk 123D circuits which is an online PCB-design tool [92]. Figure 11-3 illustrates the initial sequence of PCB-design, every design processes are based on the schematic, which is based on the schematic in Figure 11-2.

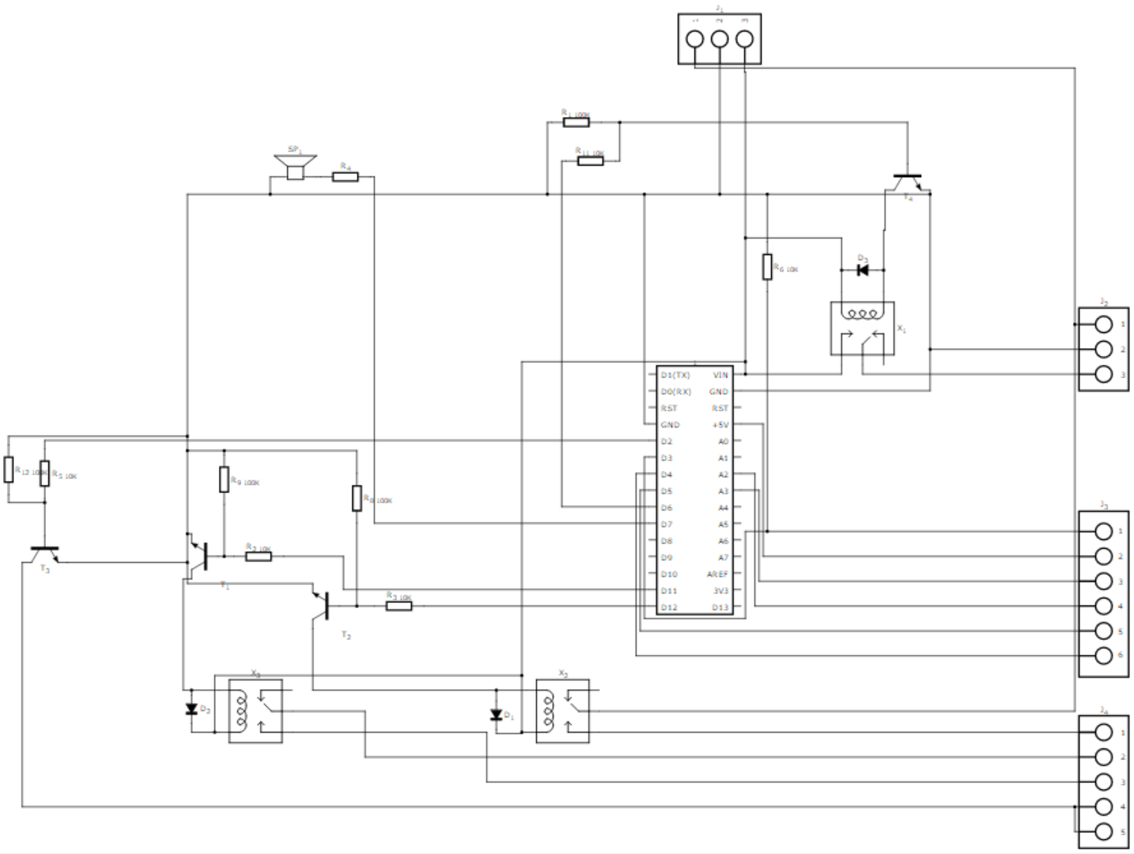


Figure 11-3. Initial circuit drawing in 123D circuits.

Further processes included a workspace to drag and drop component footprints, and adjusting the shape and size of the PCB-board shown in Figure 11-4. Typical design techniques include making horizontal traces on the front of the board, and vertical traces on the back. This is to reduce the amount of conflicts and “through holes” which is small drilled connections containing copper cylinders and work as a conductive connection between the front and back plate. The actual PCB is dual-sided plated through hole (PTH) type (“2001 layup”) with thickness 1.6 mm and 35µm copper layers.

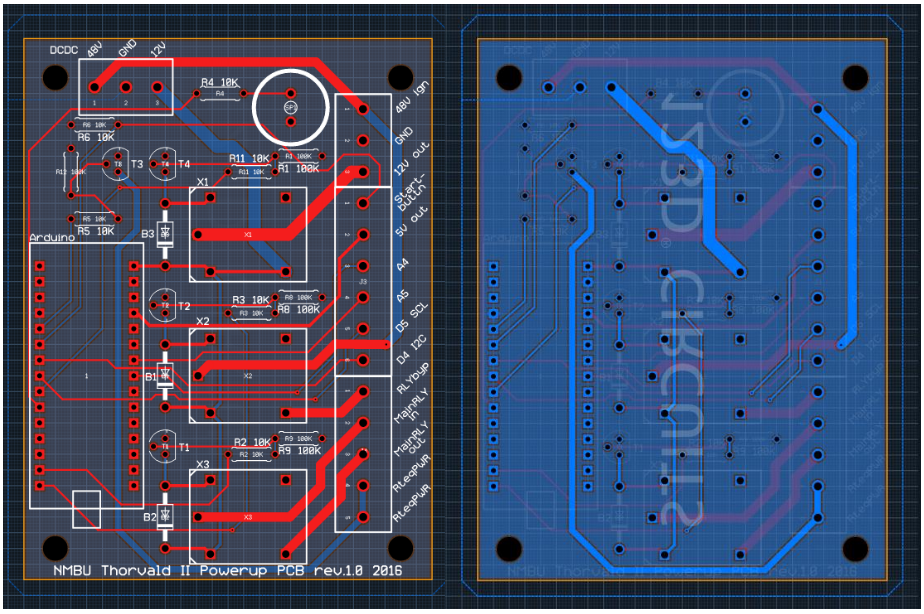


Figure 11-4. Illustration of the top and bottom layers of the PCB board. The horizontal and vertical traces are visible.

11.3. Calculations

Typical calculations for PCBs are trace widths that with the thickness of the copper layer describes the cross sectional area of the conductor [93].

$$W = ((I/(k \cdot (\Delta T)^b))^{1/c})/t \tag{11.19}$$

Where:

$W =$ Trace width
$I =$ Current
$k =$ 0.024 (constant for external layers)
$\Delta T =$ Tolerable temperature increase
$b =$ 0.44 (constant for external layers)
$c =$ 0.725 (constant for external layers)
$t =$ Thickness of copper layer

An example of a trace with calculation based on the most powerful component, the 60 W power supply, the widest copper trace is calculated:

$$W = ((5\,A/(0.024 \cdot (\Delta 20\,°C)^{0.44}))^{1/0.725})/1.38\,mils = 71\,mils$$
$$W = 71\,mils$$

This means that the PCB trace width of 80 mils is within values.

11.4. Product Architecture

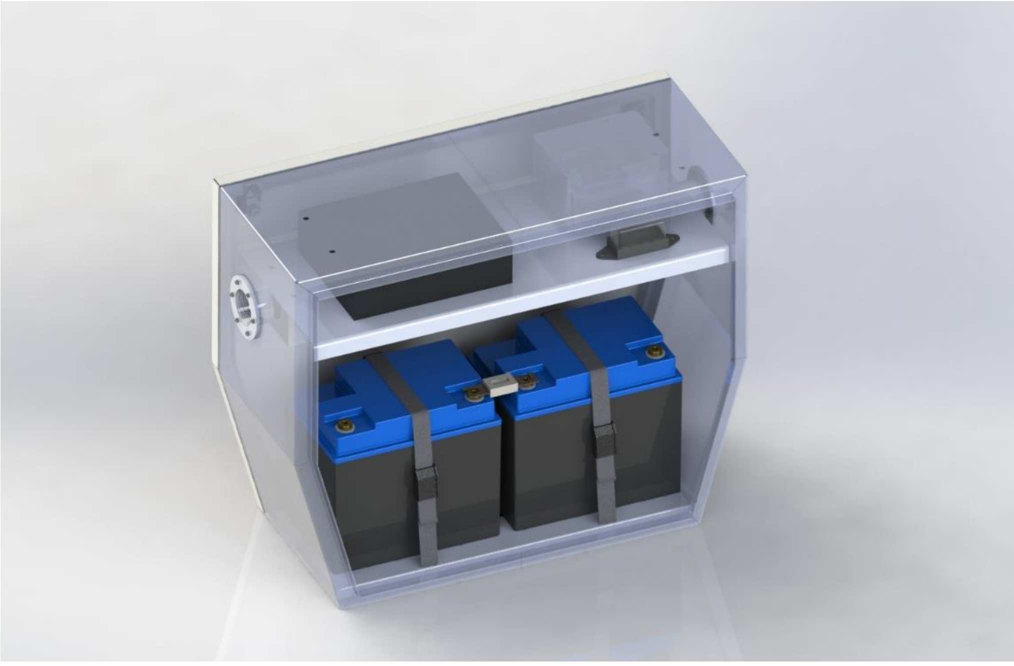


Figure 11-5. Electronic components mounted inside the electronic compartment.

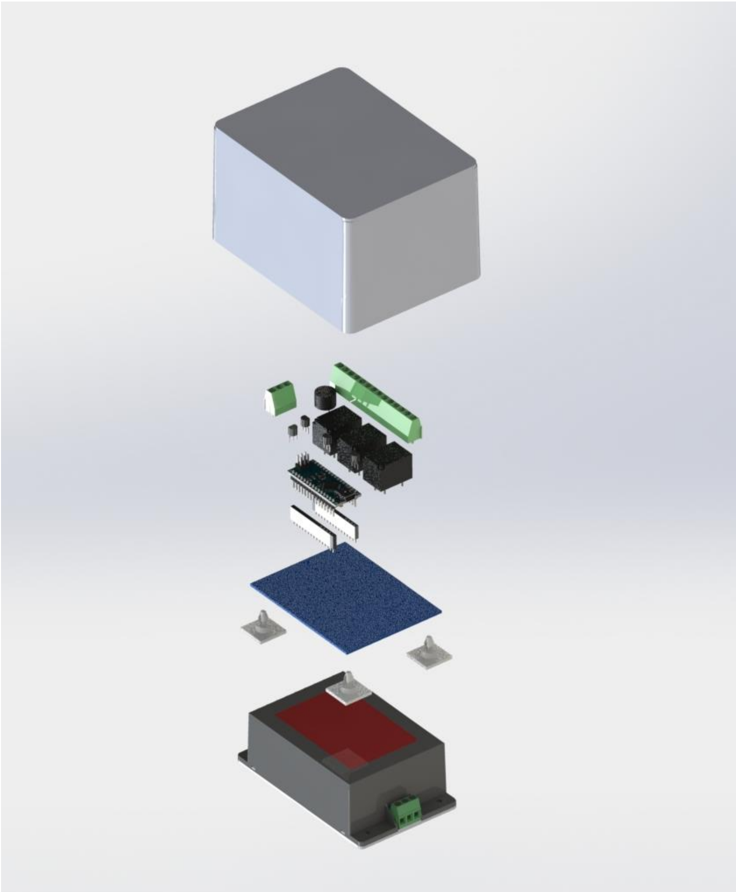


Figure 11-6. Overview of the electronic composition of the power up system.

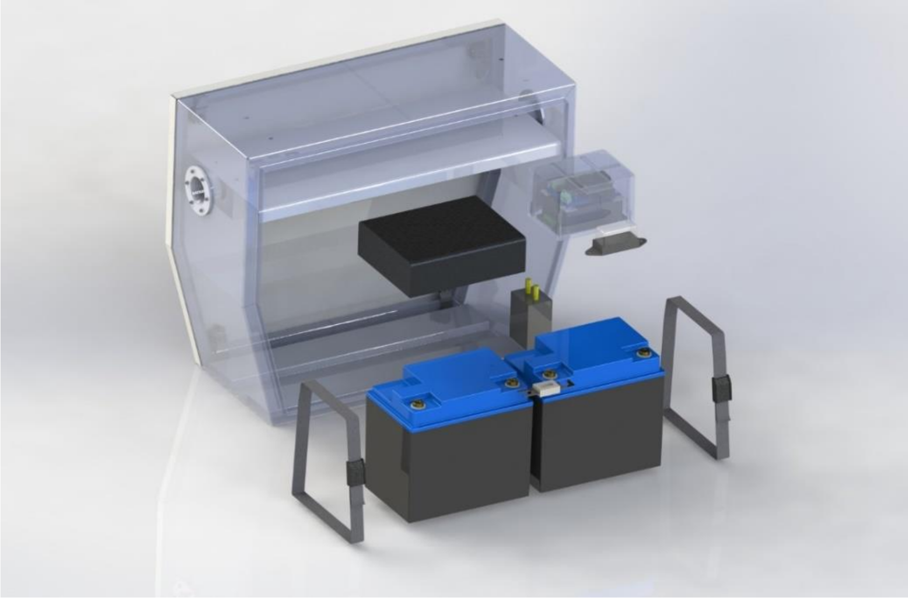


Figure 11-7. Components taken out of the box, revealing the batteries, battery strap, fuses, contactor relay, and waterproof box of the computer.

11.5. Safety

Safety is often an issue that is neglected, though it is the most important one. This master thesis is about the design of a robot, which naturally, is in motion. Even if the system is not driving very fast, or is in automotive mode, there is still dangers of getting squeezed, overrun, getting electrical shocks and so on. Even in a safe environment, of the lab, accidents can happen. To help and promote a safe robotic environment, a handful of issues need to be looked at.

Emergency Stop Button
Thorvald II is equipped with two emergency stop buttons. By pushing at least one of these buttons the power to the main relay is cut, stopping all power to the motor controllers.

Figure 11-8. Emergency stop button [94].

Conductive Insulation for Electronic Compartment
As the electrical compartment is made of high conductive aluminum material, chances are just like on a car, that a tool, wrist watch and other items can cause severe short circuiting. To reduce this risk, every positive node of 48 VDC battery voltage should be

concealed or insulated to avoid sudden contact. The electronic compartment should also have protective layers of paint, and I recommend to paint the insides by a thick layer of Plasti-Dip rubber coating or similar.

Warning Signs

By placing warnings signs, nearby people can avoid not so obvious dangers. These dangers include the danger of pinch hazards and more. Signs can also inform about the operation of an automotive robot for keeping distance.

Safety Strobes

To get everyone's attention, especially at night operations, yellow strobe lights could be fitted on the robot. One on each wheel module could be a natural placement.

Bumper System

A bumper system could be made by either 2D laser radar system, sonars or other forms of distance measuring sensor. This way, the robot can be programmed to automatically stop when an object or a person is near. Even physical bumpers using micro switches can easily be made.

12. Production Process

12.1. Components Configuration

The NVidia Jetson TX1 was really hard to get hold of as is a brand new technology fresh from the factory. By the help of Lincoln University in England, we were able to get hold of some modules. The TX1 came preconfigured with Ubuntu, which is a Linux-based free operating system. The installation of ROS went problem free. Figure 12-1 shows the process of ROS installation on the NVidia module.

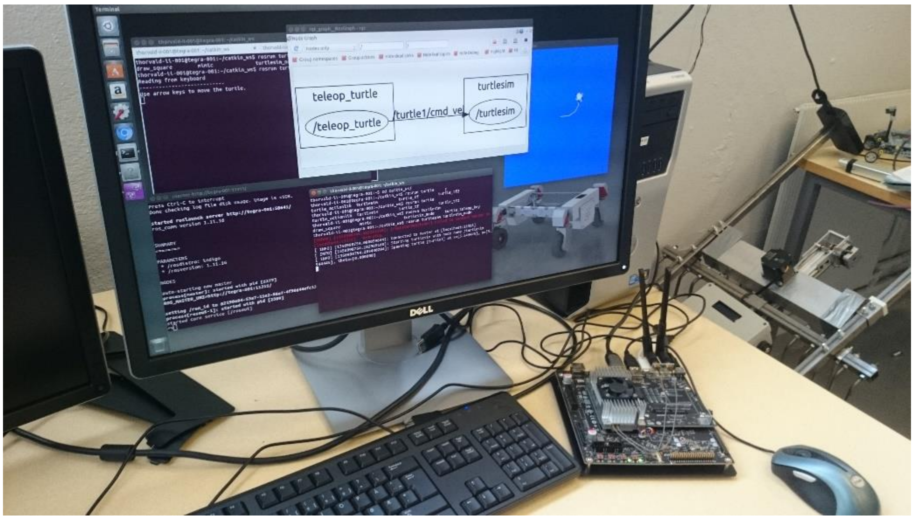


Figure 12-1. The image shows the configuration of the NVidia Jetson TX1 with ROS installed. The desktop shows Ubuntu Linux with the ROS turtle simulation up and running.

12.2. Assembly

I did the PCB assembly on an ESD-protective lab at NavSys AS, which is a navigation and geomatics dealership and R&D company. Figure 12-2, Figure 12-3 and Figure 12-4 illustrates the PCB production process.

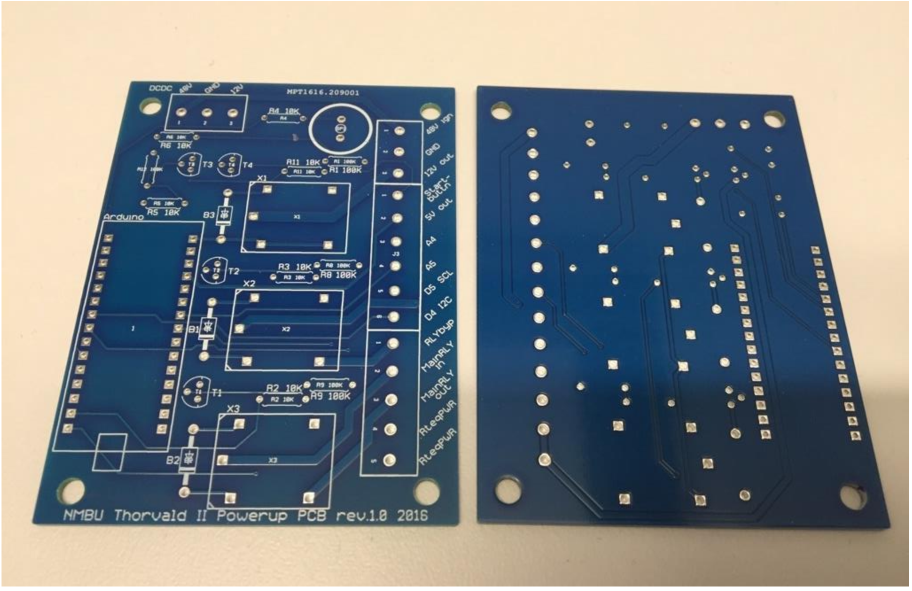


Figure 12-2. Front and back power up PCBs as delivered from Elprint AS.

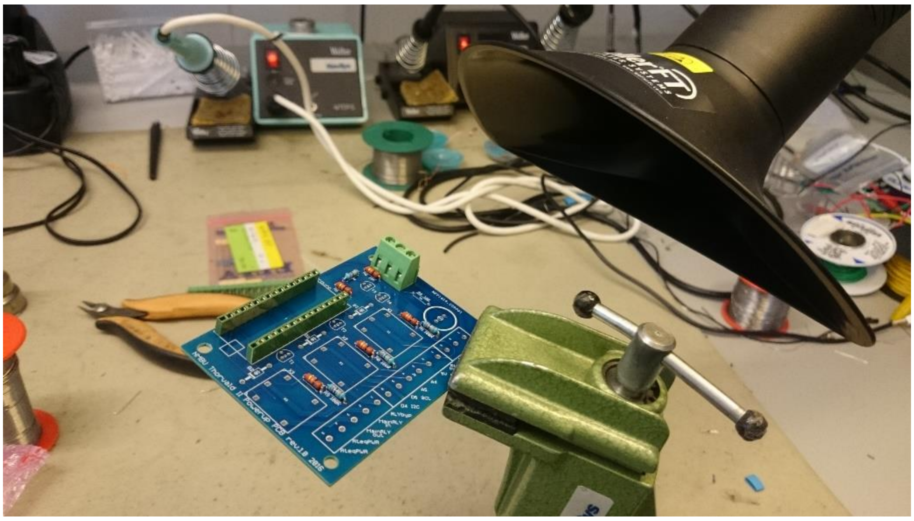


Figure 12-3. Soldering Process on a ESD-protective lab and proper ventilation.

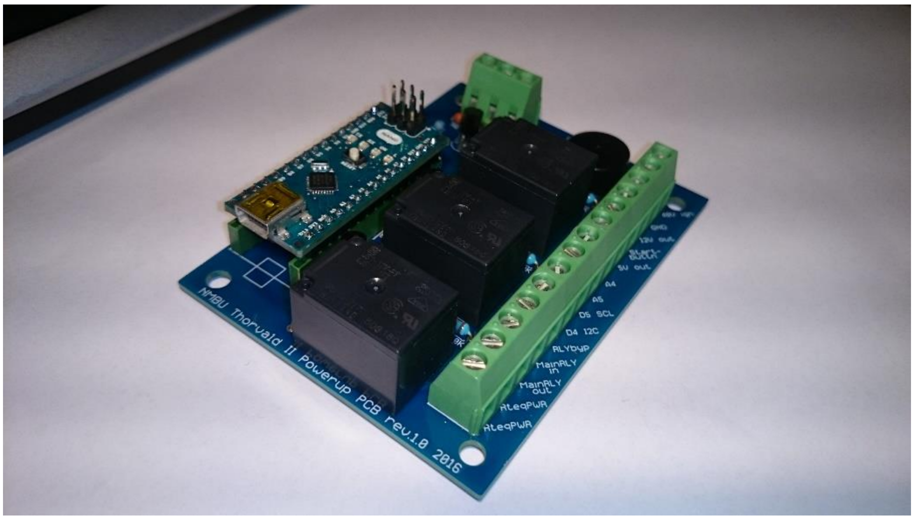


Figure 12-4. Final assembly of the power up PCB.

12.1. Costs

Table 12-1. This table shows the costs of the electrical system for one Thorvald II unit with the main configuration.

Specification	Single Price [NOK]	Units/hours	Sum [NOK]
Jetson TX1	3000	1	3000
PCB	330	1	330
PCB tooling (onetime costs)	1250	1	1250
Batteries	8000	4	32000
Components	4000	-	4000
Wires	500	1	500
SUM			**41080**

12.2. Experiences

Since the NVidia Jetson TX1 module is so new and fresh from the factory, we will be one of the few first system developers who plough our way through unknown terrain and make way for others. It is expected to meet problems and challenges during the development. We have already met a problem concerning the use of CANopen due to the temporally 32-bit kernel (Operating system). These drivers only work on 64-bit kernels, but I'm sure we will be able to make our way around the problem. NVidia is currently configuring a 64-bit kernel for the TX1 module, so it is expected to make everything work in the near future.

The process of PCB design was a lot more work than previously thought. Firstly, schematics needed to be exactly correct for the PCB to be correct. Secondly, a lot of the components footprints needed to be customized, as there were incomplete libraries available. For the available library footprints, all of them needed to be double checked for being correct, as some of them were not. The PCB Gerber design file was to be sent to NavSys, who has long experience of PCB design, for checking. When opening the file in another, web-based tool, MACAOS, it was revealed that a few diode holes that had no drill hole. After correcting the footprint, everything seemed fine. However, by finally ordering the PCB, quick delivery from Taiwan and the soldering work went like a charm.

Based on the work done, there will be a lot of work assembling the wires and harnesses even with quick screw connections and so on. Even so, dependent of chassis status and some hard work and long hours, I'm confident of getting the job done.

13. Conclusion of Part Two

13.1. Results

Most of the components for the electric compartment have arrived. Batteries, computer electronic components, and so on. But without a robot, this is just a pile of parts for the moment.

This didn't stop us from making other things ready. Even if the robot is not built yet, there is multiple things to start with. The PCB was easy to solder, and everything went smoothly at the lab. Early multi-meter tests that are conducted on the PCB assembly show promising results.

The configuration and installation of ROS on the computer went fine, but due to some technical difficulties with CANopen installation, this activity is as explained elsewhere currently on hold.

13.2. Future Work

When the robot is finally assembled, the remaining work is to mount the electrical system in a neat and tidy harnesses. Even though it seems tempting to put harnesses through the tube frame, this could make it harder to do later wheel base adjustments. It is recommended to use plastic cable channels and adhesive strips-holders on plain surfaces. Also to be considered is wire construction (wire jacket, wire gauge and number of wire strains), routing for moving wires, EMI shielding for noise sensitive signals and protection against wire chafing.

As the computer of choice has no enclosure, suitable casings with the a IP33 IP-grading needs to be found. This is determined by the computer mini-ITX format.

Fuses, wire thicknesses and wire construction needs to be correctly chosen along with the building process. I suggest checking tables for wire lengths and the amount of power needed at the consumer end for the correct dimensioning. Although the electronic shelf is initially designed with aluminum, it could be a better choice to use a plastic, polycarbonate shelf to avoid short circuiting.

The batteries should be mounted in a securely way to avoid any movements. I suggest using plastic straps with plastic buckles secured around the drain plate on the bottom of the container. In addition, to avoid sudden tool contact on the batteries I suggest to cover the poles and fuses with a battery pole protector. It could also be beneficiary with a transparent polycarbonate sheet, that can be bent as a U-shape lid over the batteries.

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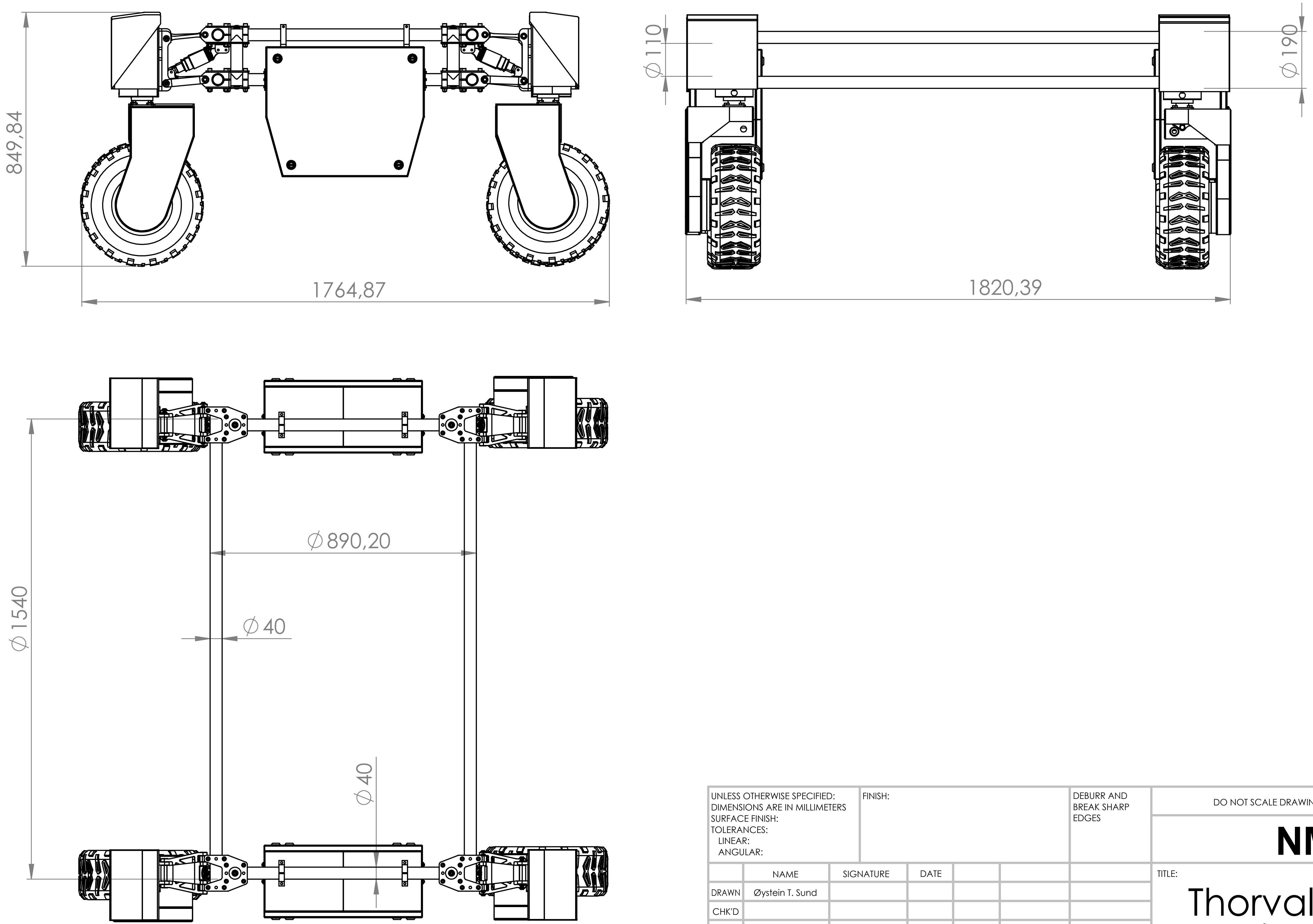
Apendix

- 30 Drawings
- 1 Schematic
- USB containing full format drawings, DXF and STL formats



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

NMBU

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

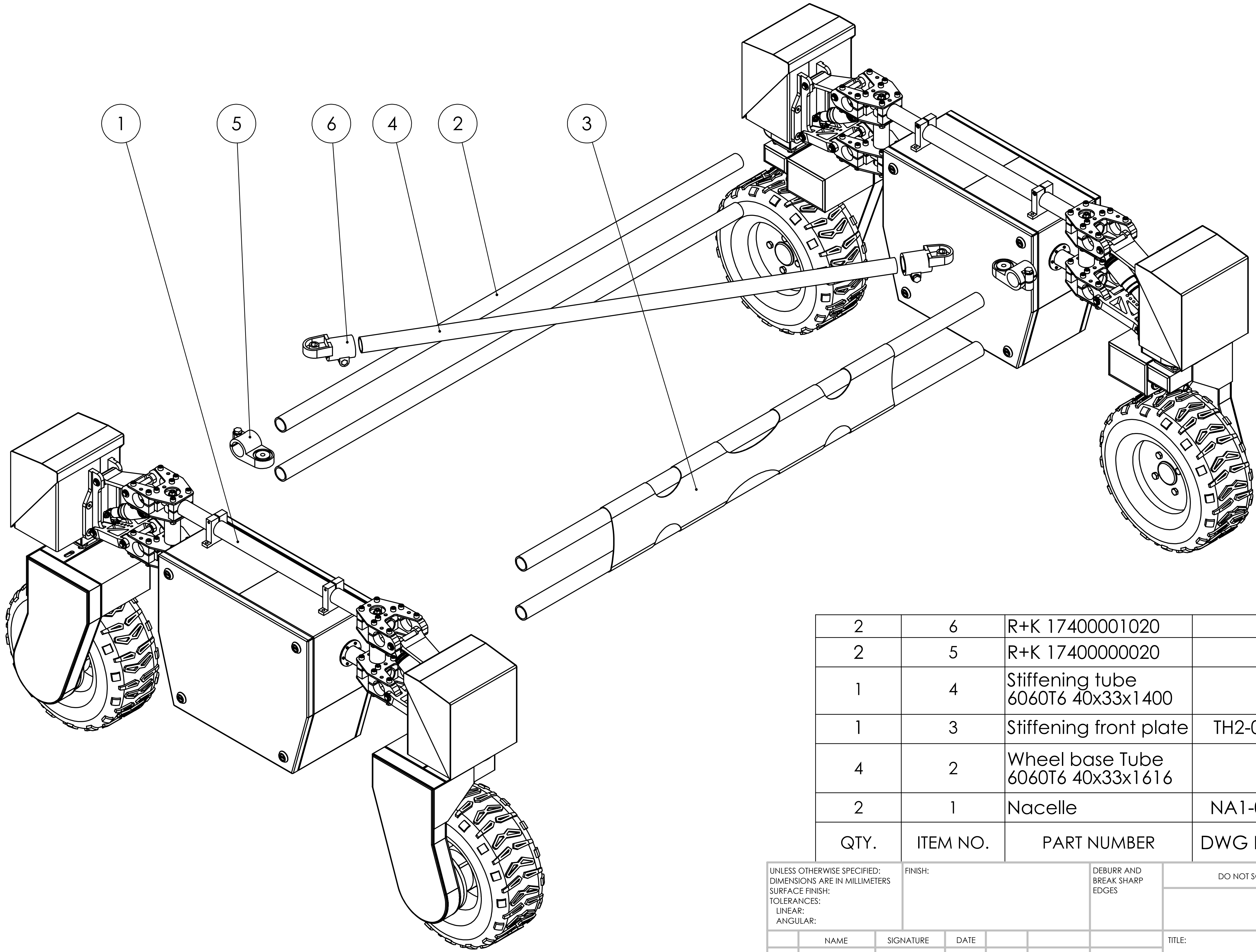
Thorvald II main Dimensions

DWG NO.

A3

SCALE:1:15

SHEET 1 OF 1



QTY.	ITEM NO.	PART NUMBER	DWG No.	DESCRIPTION
2	6	R+K 17400001020		
2	5	R+K 17400000020		
1	4	Stiffening tube 6060T6 40x33x1400		Wheel base - 100mm
1	3	Stiffening front plate	TH2-01	
4	2	Wheel base Tube 6060T6 40x33x1616		Wheel base + 116mm
2	1	Nacelle	NA1-00	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

NMBU
Thorvald II

MATERIAL:

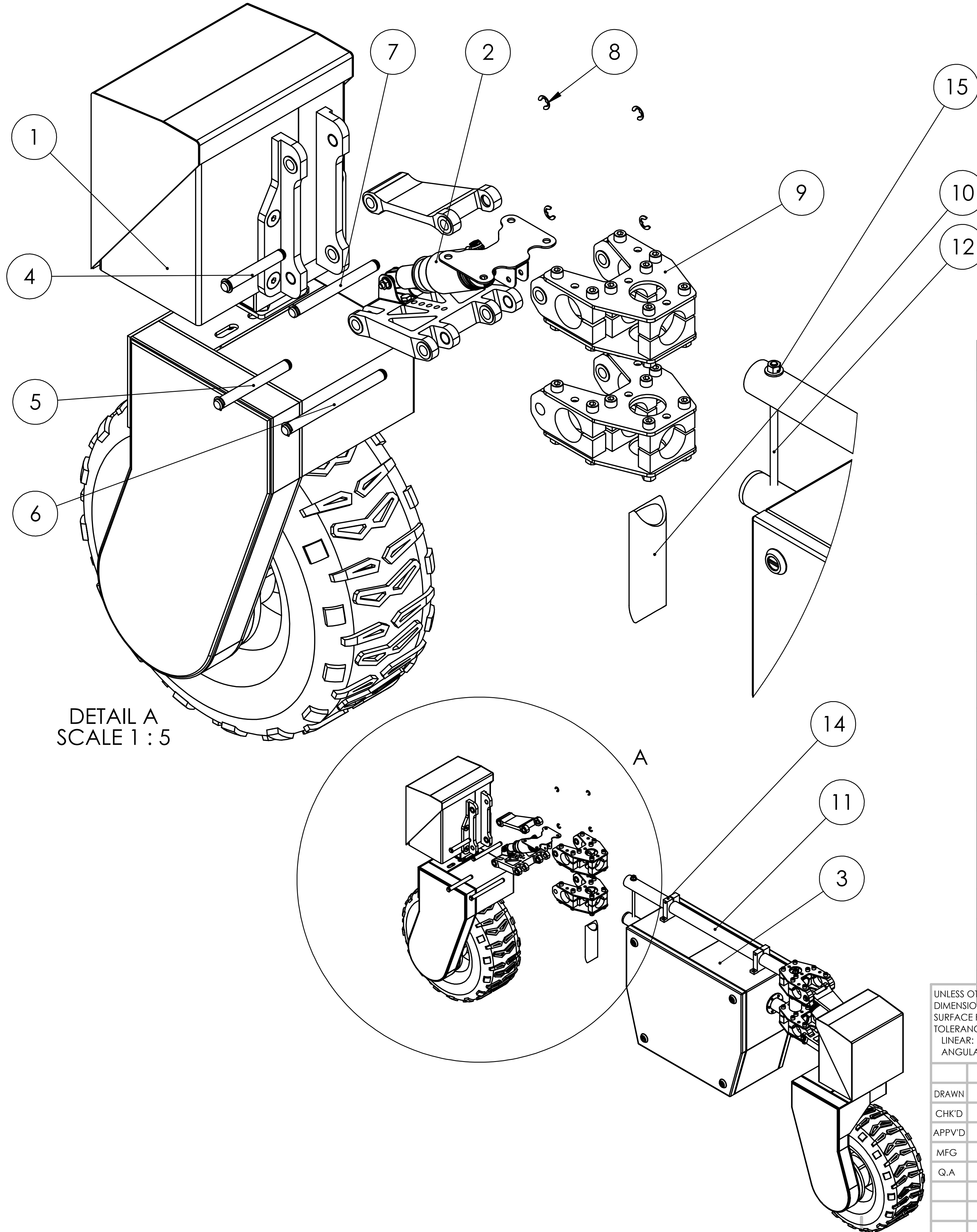
DWG NO.
TH2-00

A3

WEIGHT:

SCALE:1:10

SHEET 1 OF 1



QTY.	ITEM NO.	PART NUMBER	DWG No.
4	14	M6 Nut	
2	13	R+K 52400011030	
2	12	Thread bar M10 220mm	
2	11	Nacelle Tube 6060T6 40x33x810	
2	10	Vertical spacer	NA1-01
4	9	Tube T-Connection	TT1-00
16	8	12mm e-clip	
2	7	Upper nacelle hinge pin	SA1-08
2	6	Lower nacelle hinge pin	SA1-07
2	5	Lower tower hinge pin	SA1-05
2	4	Upper tower hinge pin	SA1-06
1	3	Electronic Compartment	EC1-00
2	2	Suspension Assy	SA1-00
2	1	Suspension Brackets on wheel module	SB1-00

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

NMBU

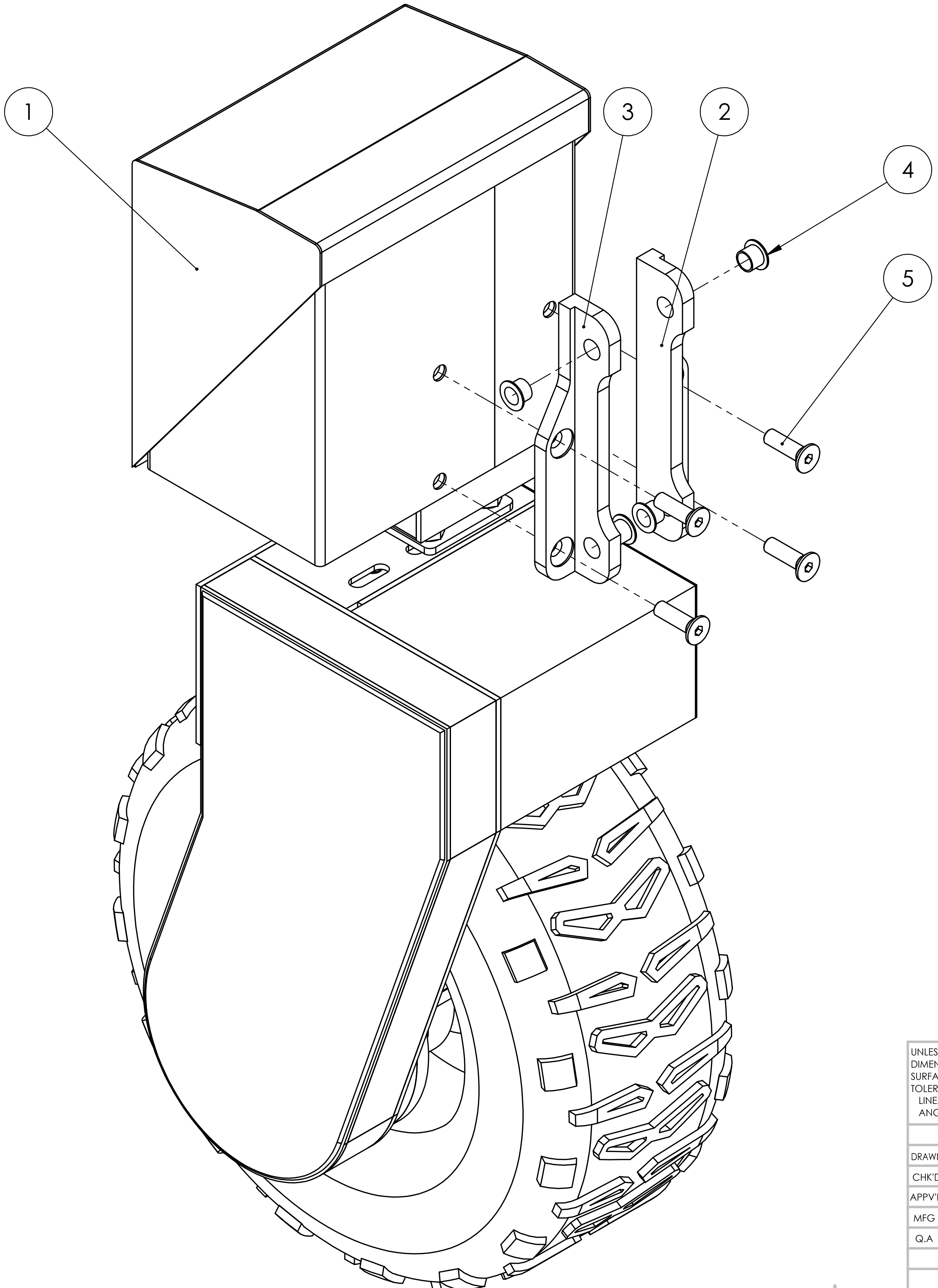
Nacelle Assembly

DWG NO. NA1-00

A3

SCALE:1:15

SHEET 1 OF 1



QTY.	ITEM NO.	PART NUMBER	DWG No.
4	5	ISO 10642 - M10 x 35 --- 35N	
4	4	SKF PPMF1210	
1	3	LH suspension L-bracket_10mm	SA1-03
1	2	RH Suspension L-bracket_10mm	SA1-04
1	1	Wheel Module	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

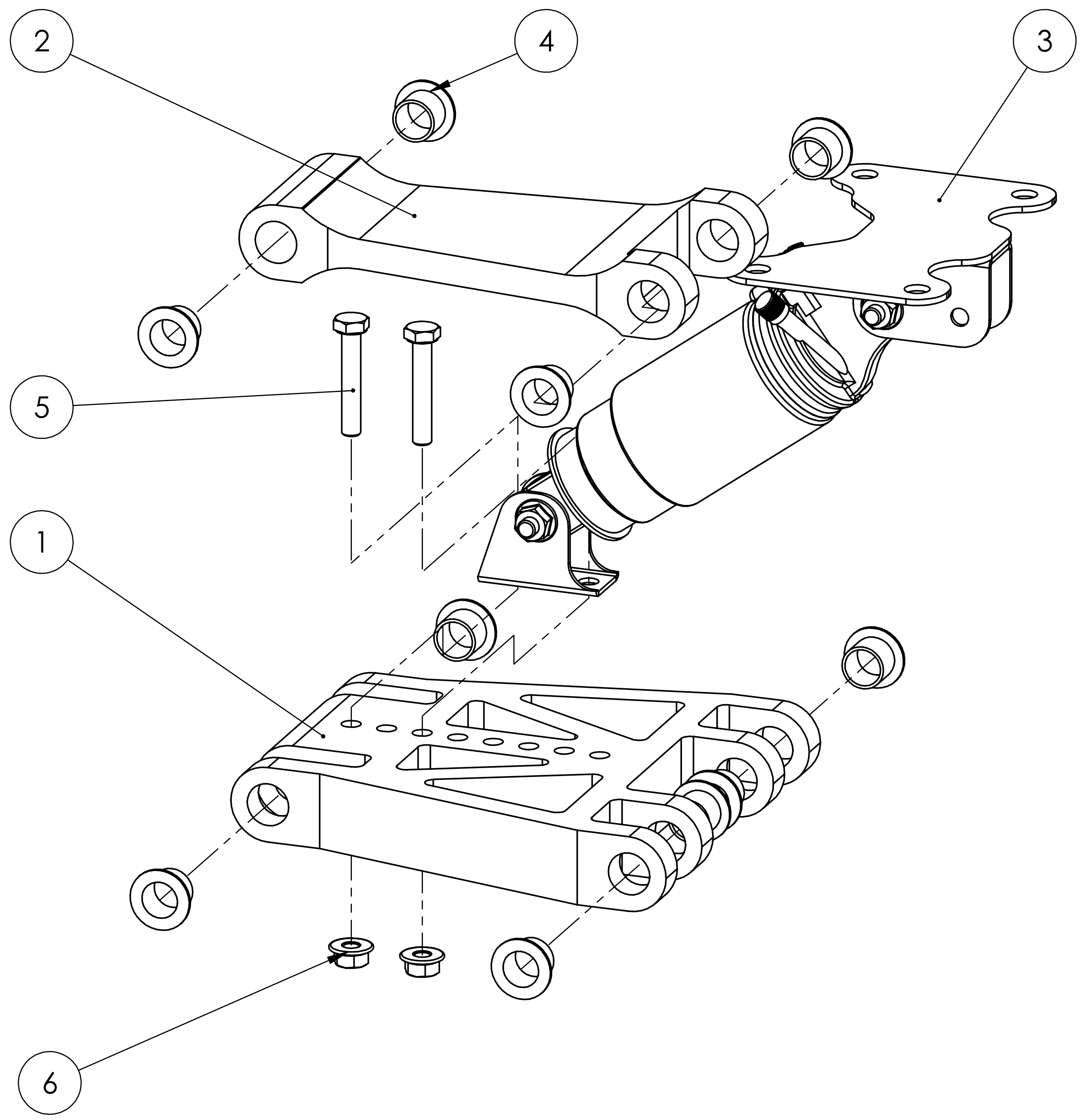
NMBU
Suspension Brackets

DWG NO. SB1-00

A3

SCALE:1:3

SHEET 1 OF 1



QTY.	ITEM NO.	PART NUMBER	DESCRIPTION
2	6	M6 Nut	
2	5	M6 Bolt 35mm	
10	4	SKF PPMF1210	
1	3	270416Damper 165x37_5	
1	2	270416Suspension bridge 2	SA1-02
1	1	270416suspension bridge heavy duty	SA1-01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1B

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

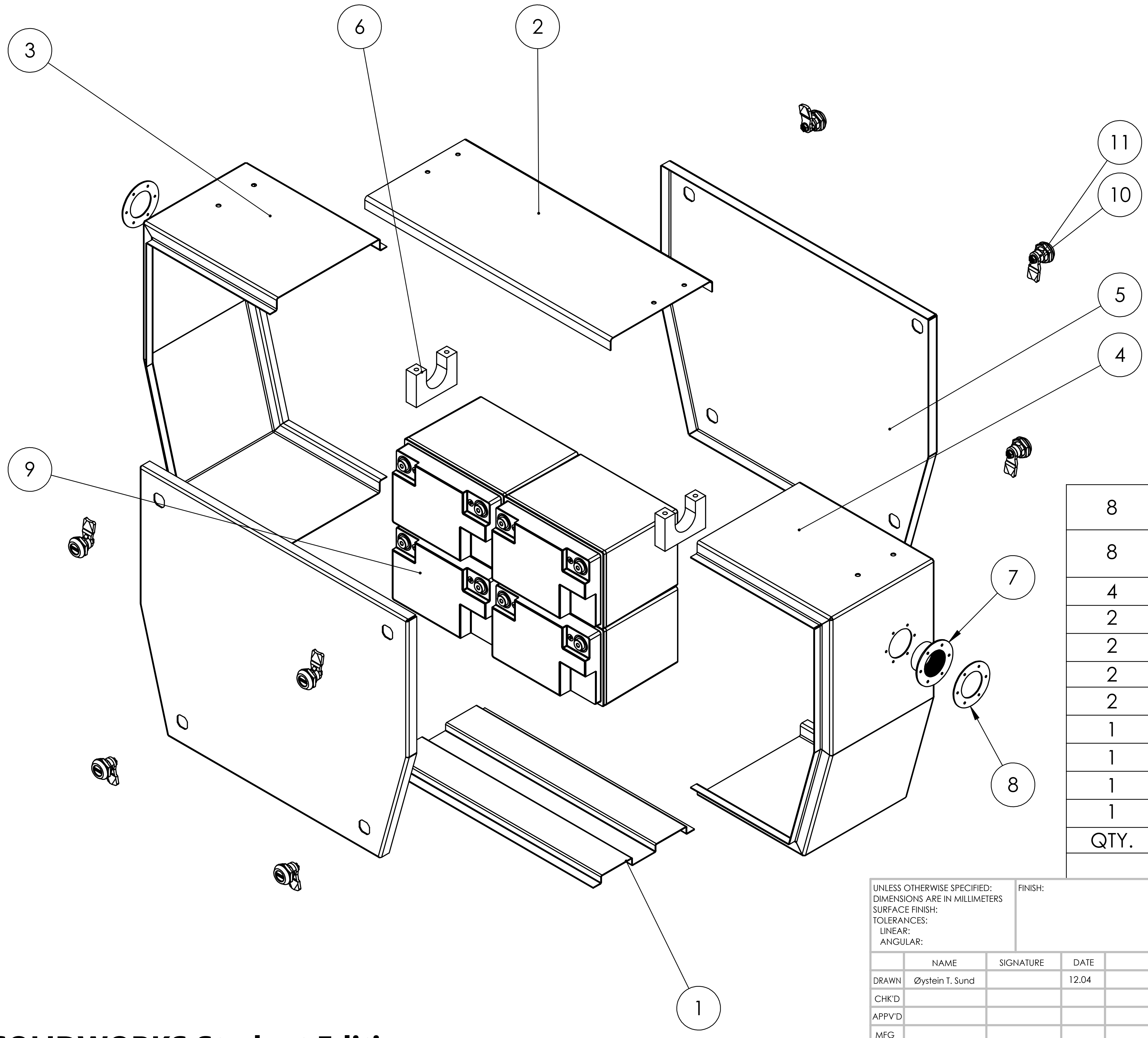
NMBU
Suspension Assy

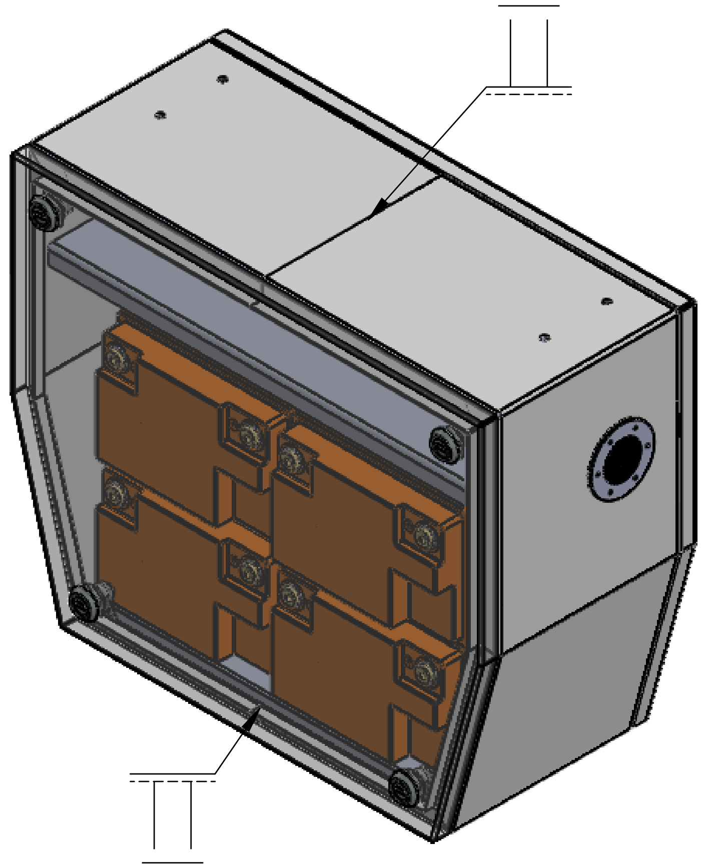
DWG NO.
SA1-00

A3

SCALE:1:2

SHEET 1 OF 1





QTY.	ITEM NO.	PART NUMBER	DWG No.
8	11	K0522_20181 slotted lock KIPP	N/a
8	10	0K0523.135X205 lock tongue KIPP	N/a
4	9	Batteries	N/a
2	8	Tube gasket plate	N/a
2	7	Tube gasket	N/a
2	6	Shelf mount	N/a
2	5	EC Lid	EC1-05
1	4	RH EC box	EC1-04
1	3	LH EC box	EC1-03
1	2	EC shelf	EC1-02
1	1	Drain plate	EC1-01

BOM Table

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

NMBU

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		12.04
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Thorvald II
Electronic Compartment
BOM

DWG NO. EC1-00

A3

SCALE:1:6

SHEET 1 OF 1

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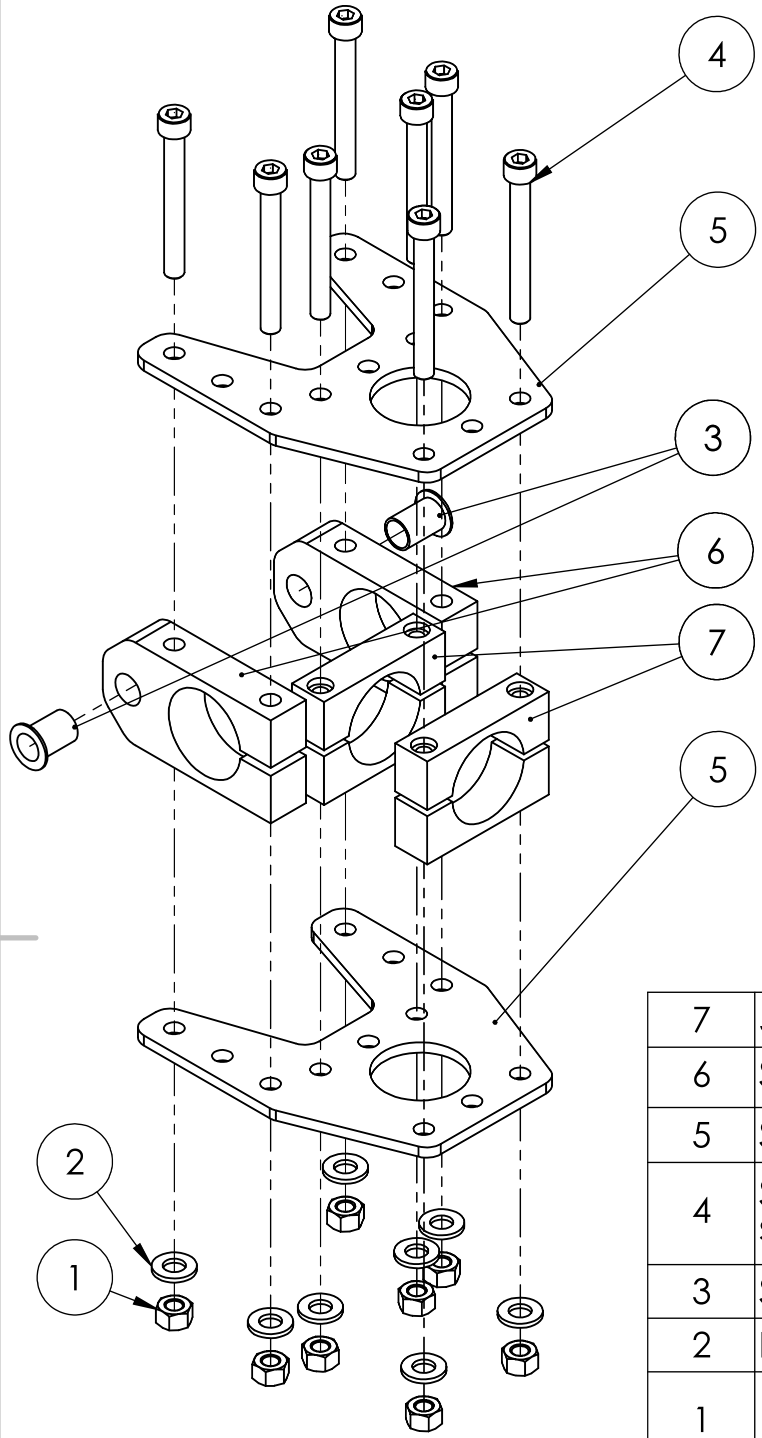

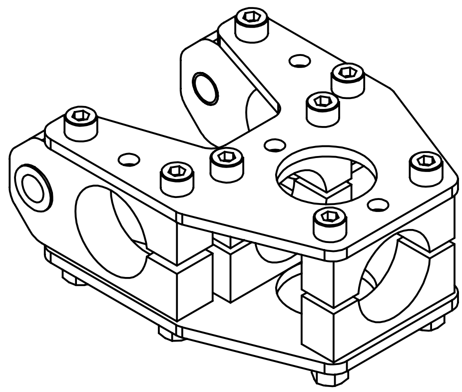

ITEM NO.	PART NUMBER	DWG No.	QTY.
7	52400002030# Milled	TT1-03	4
6	Suspension bracket	TT1-02	2
5	Sandwich T-bracket	TT1-01	2
4	Socket head cap screw M8		8
3	SKF PPM 121410		2
2	ISO 10673-9.3-S		8
1	Hexagon Nut ISO - 4034 - M8 - N		8

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE		
DRAWN	Øystein T. Sund		20.04		Tlf: 41654843
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

NMBU
Tube T-connection

MATERIAL: AL 6082T6 3mm

DWG NO. TT1-00

A4

WEIGHT:

SCALE:1:3

SHEET 1 OF 1

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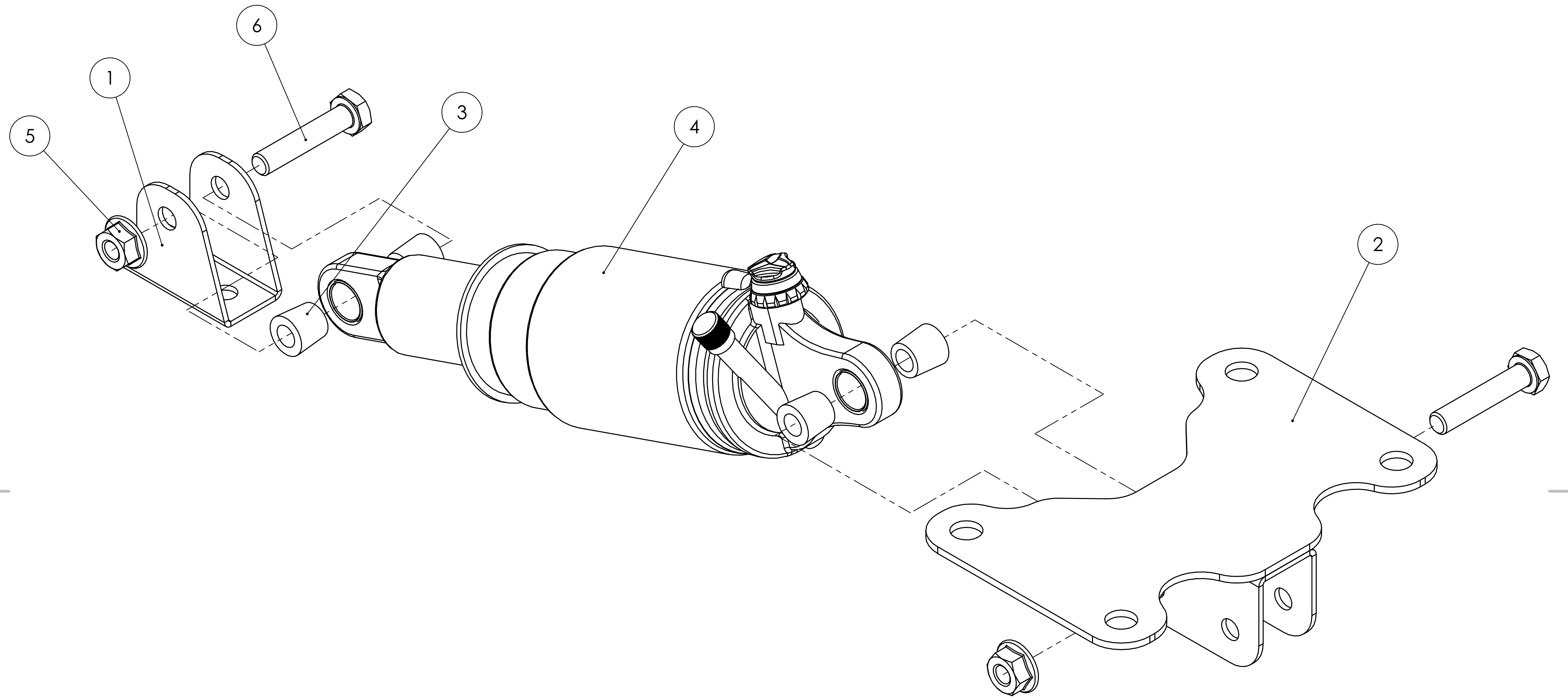


QTY.	ITEM NO.	PART NUMBER	DWG No.
2	6	ISO 4014 - M6 x 30 x 18-N	
2	5	Hexagon Flange Nut ISO - 4161 - M6 - N	
1	4	Damper	
1	3	Damper bushingD4	DA1-02
1	2	Top damper hinge bracket	DT1-00
1	1	Lower damper hinge bracket	DA1-01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

NMBU

Damper assembly

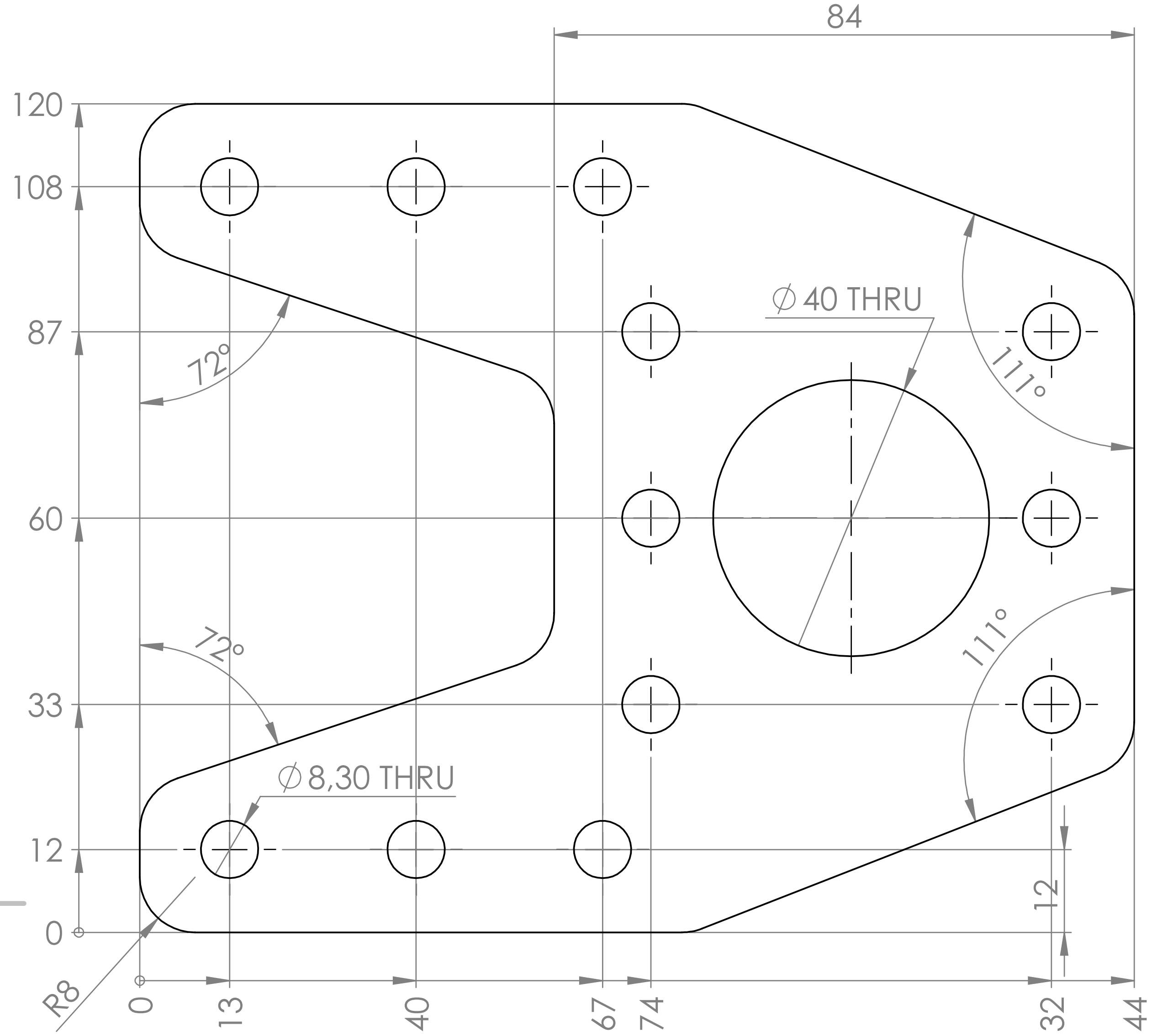
DWG NO.

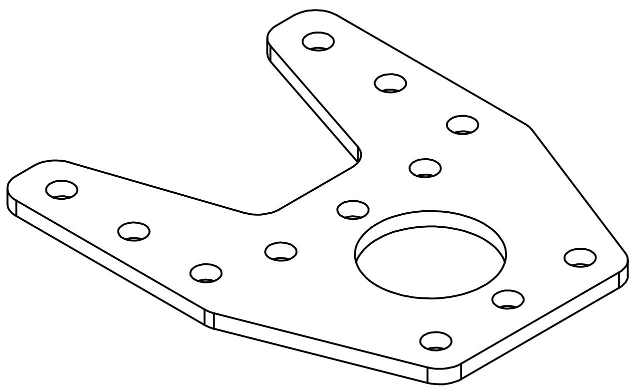
DA1-00

A3

SCALE:1:1

SHEET 1 OF 1





Fin toleranseklasse på ikke toleransesatte mål

Also availale as .dxf

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Øystein T. Sund		20.04		Tlf: 41654843	**NMBU** Sandwich T-bracket	
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: AL 6082T6 3mm		DWG NO. TT1-01	A4
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1

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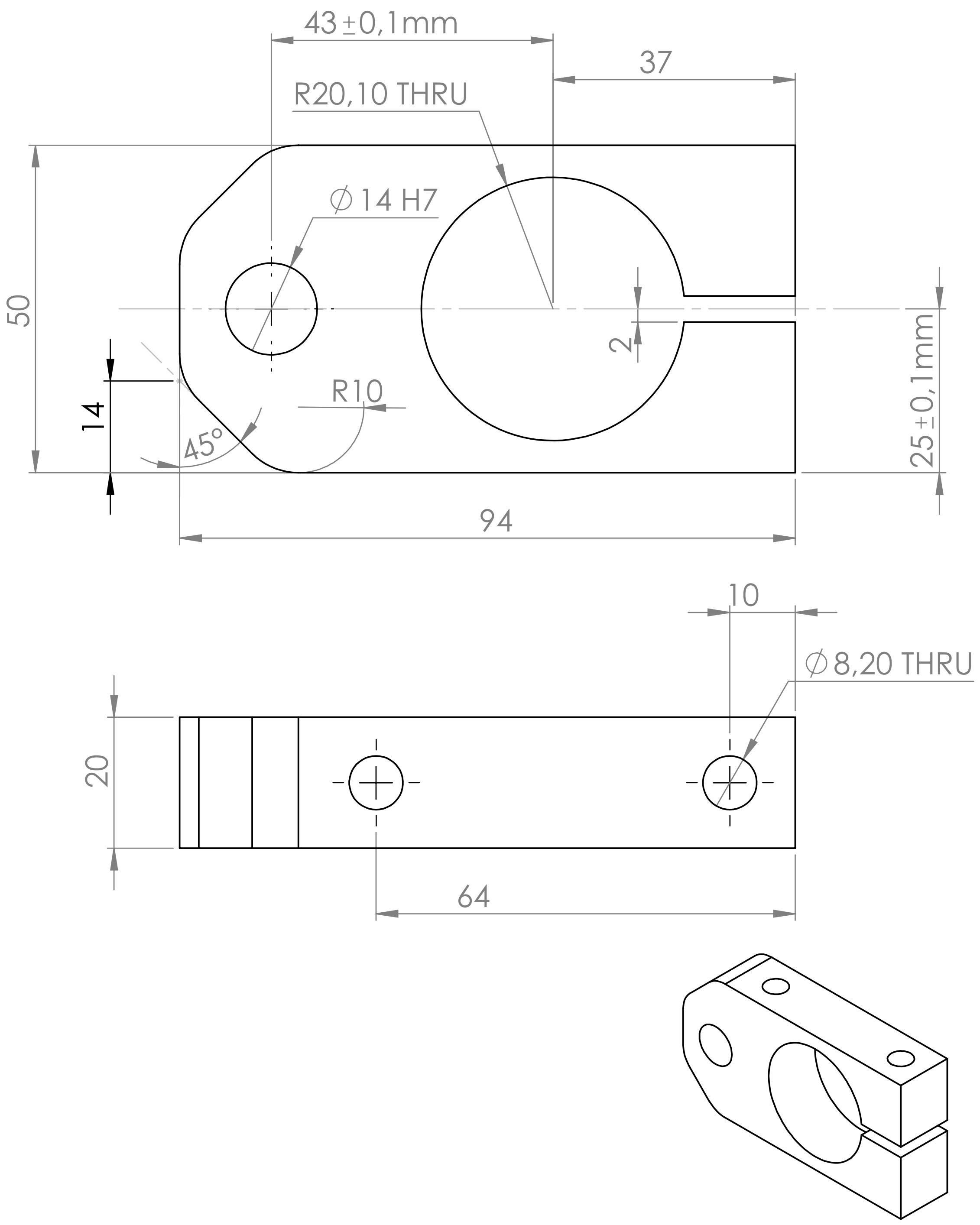

Middels toleranseklasse på ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A
	NAME	SIGNATURE	DATE			TITLE:
DRAWN	ØysteinT Sund		20.04		Tlf 41654843	**NMBU** Suspension bracket
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: AL 5xxx Skinne 50x20			DWG NO. TT1-02 — A4
			WEIGHT:			SCALE:1:1 — SHEET 1 OF 1

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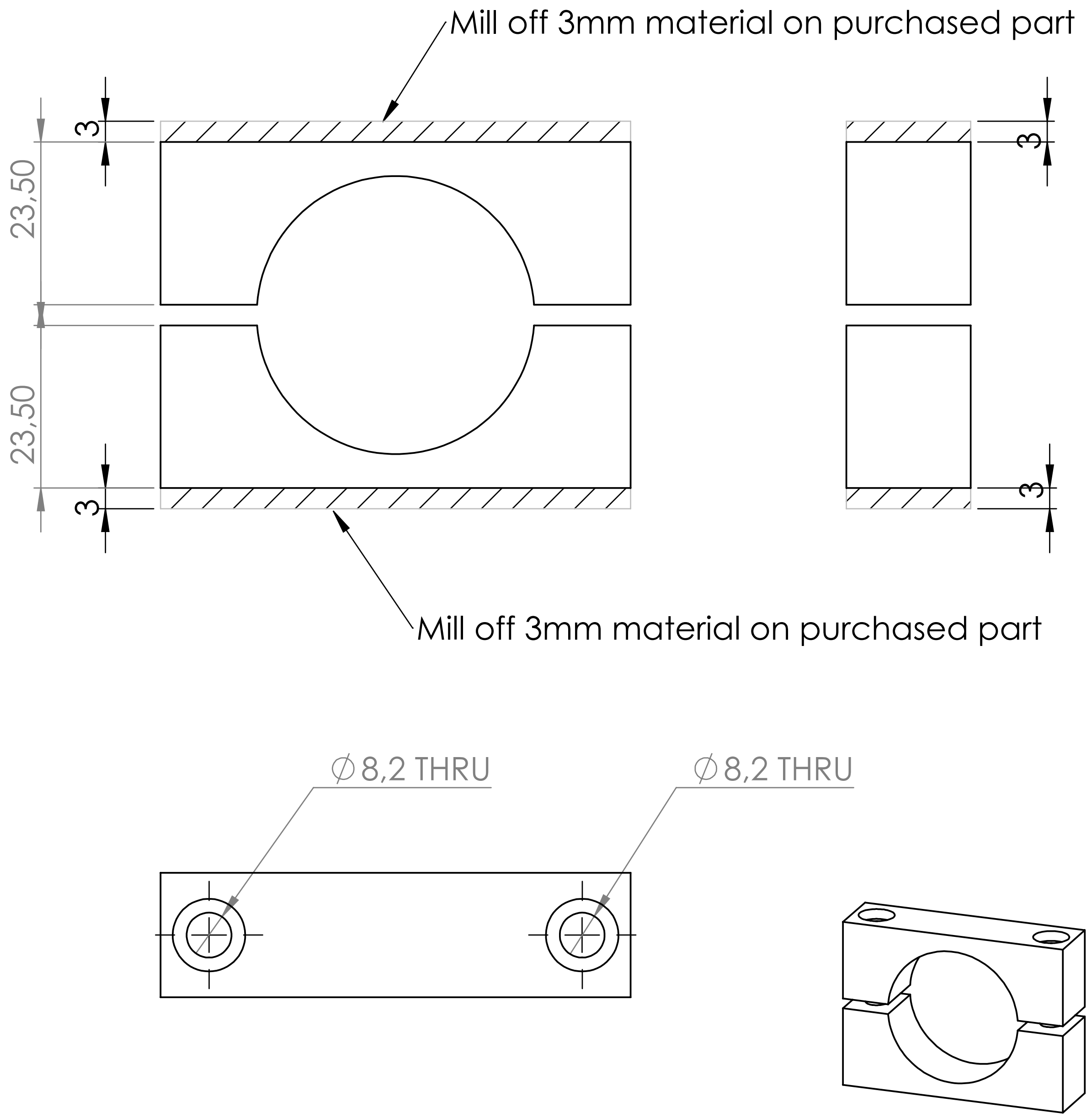

Fin toleranseklasse på ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE		
DRAWN	Øystein T Sund		20.04		Tlf 41654843
CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL: Rose+Krieger 5240002030#

WEIGHT:

TITLE:

NMBU
5240002030# Milled

DWG NO. TT1-03

A4

SCALE:1:1

SHEET 1 OF 1

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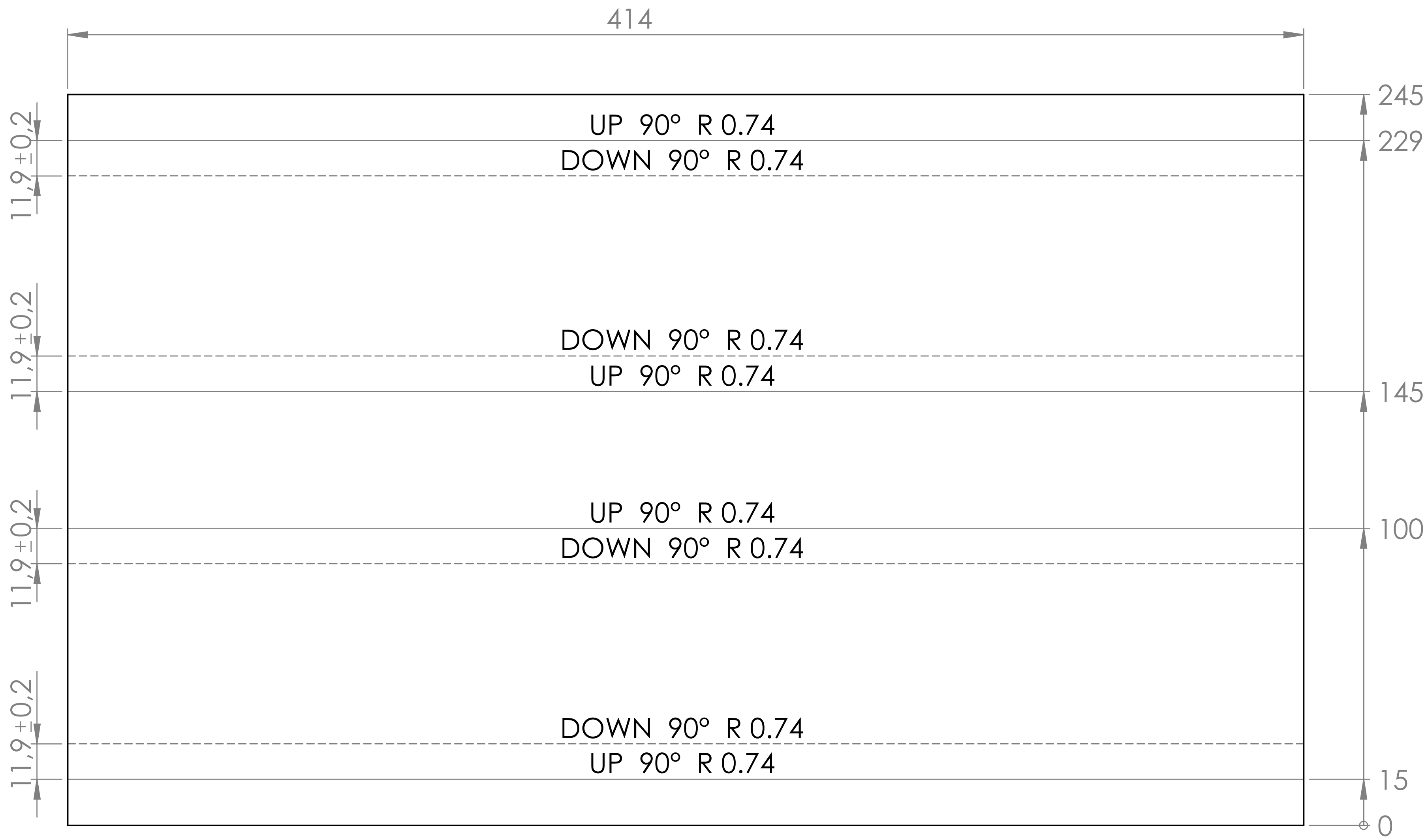

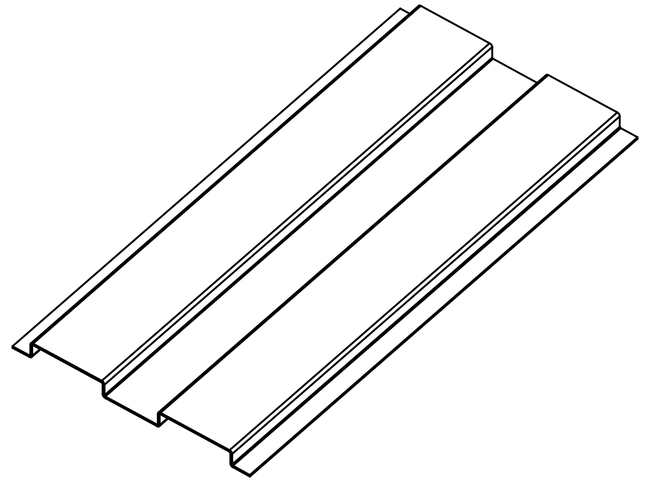

Grov toleranseklassepå ikke toleransesatte mål (NS-ISO 2768-1)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A
			NMBU	

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		12.04
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: **Thorvald II** Drain plate

MATERIAL: AL 5754 1,5mm

DWG NO. EC1-01

A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1

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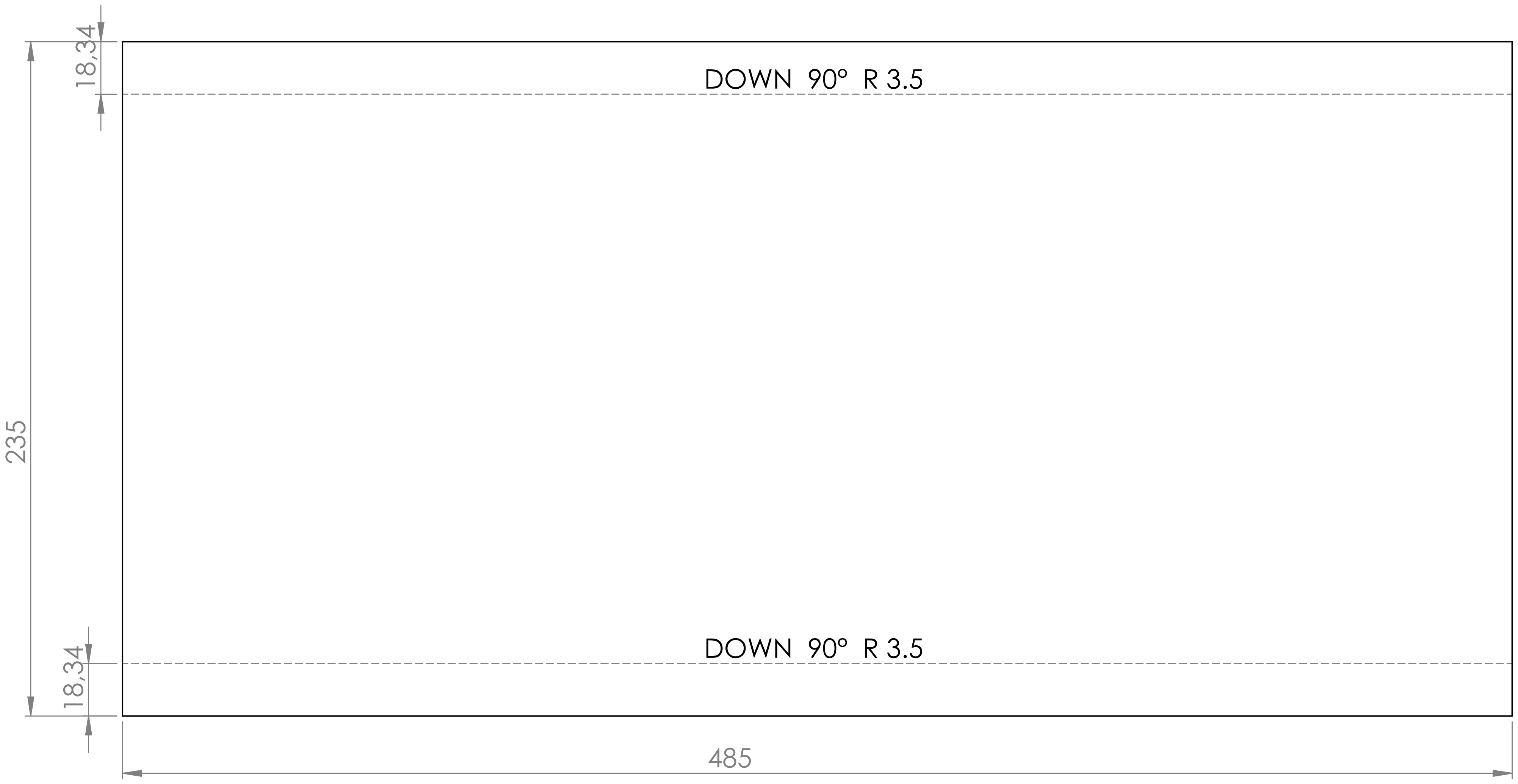

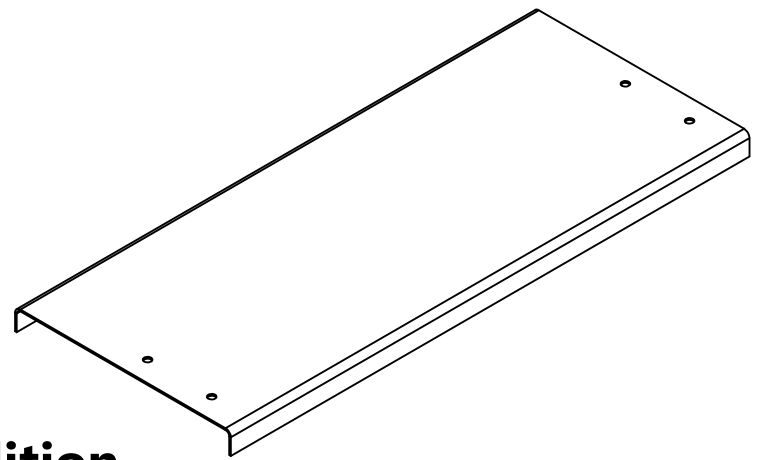

Middels toleranseklassepå ikke toleransesatte mål (NS-ISO 2768-1)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +/- 1mm ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION 1A
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Øystein T. Sund		12.04			**Thorvald II** EC shelf	
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: AL 5754 1,5mm		DWG NO. EC1-02	A3
				WEIGHT:		SCALE:1:2	SHEET 1 OF 1

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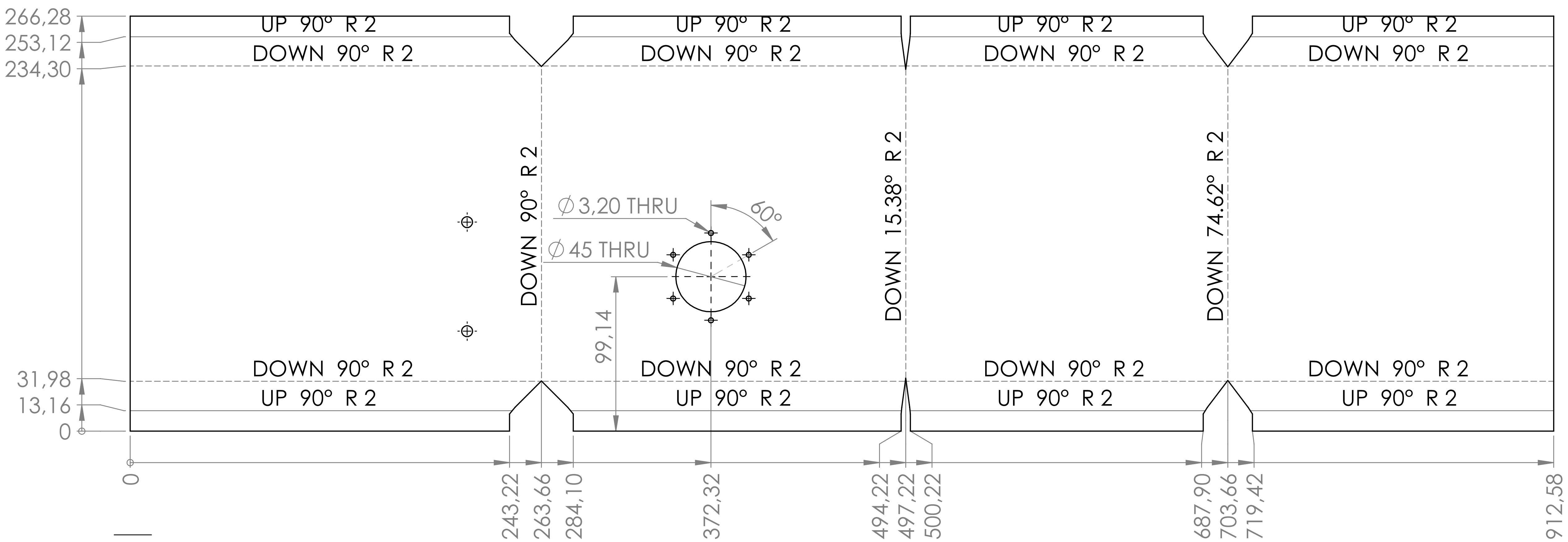

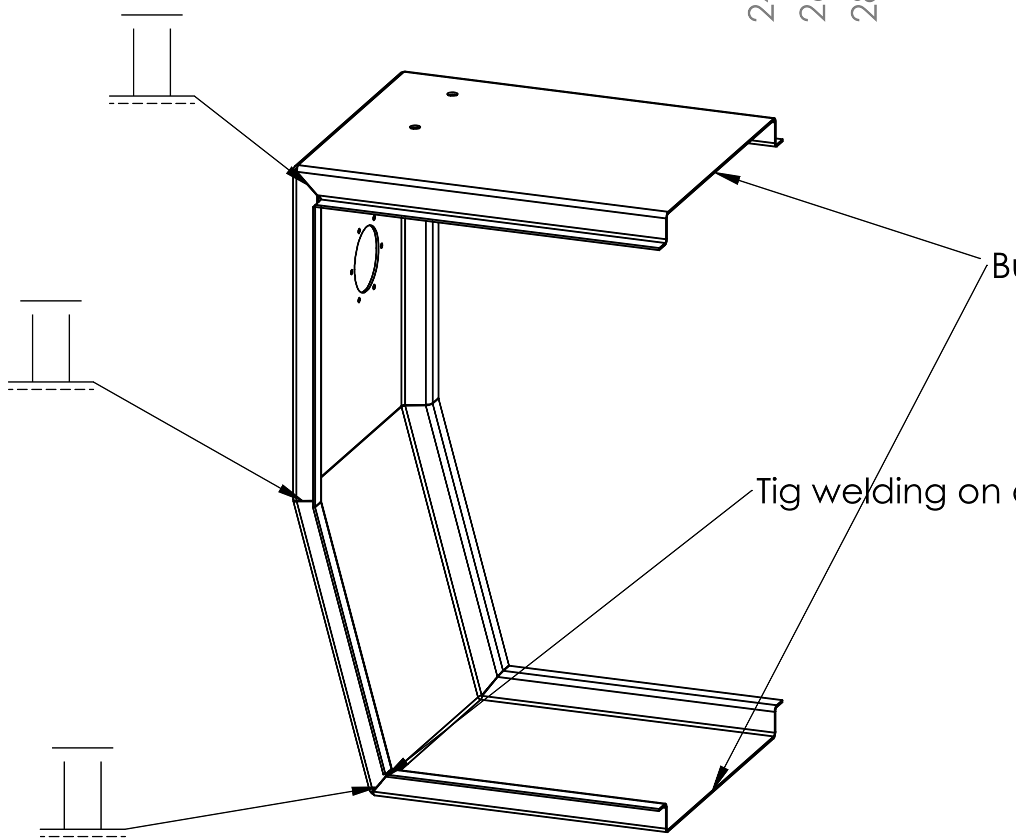

Fin toleransegrad (NS-ISO 2783-1)

Drawing also available as .dxf format

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: N/A TOLERANCES: LINEAR: +- 0,1mm ANGULAR: +- 0,1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION 1A
			NMBU

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		12.04
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: **Thorvald II**
RH EC box

MATERIAL: AL 5754 1,5mm

WEIGHT:

DWG NO. EC1-04

A3

SCALE:1:3

SHEET 1 OF 1

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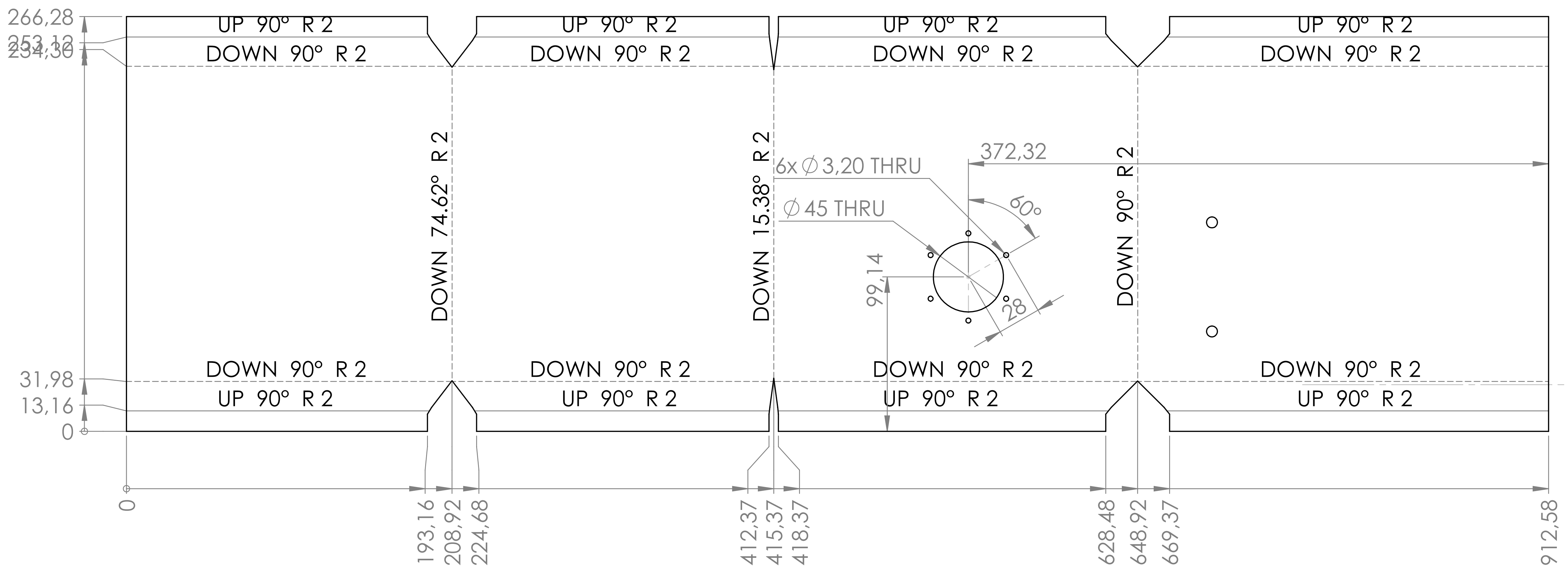
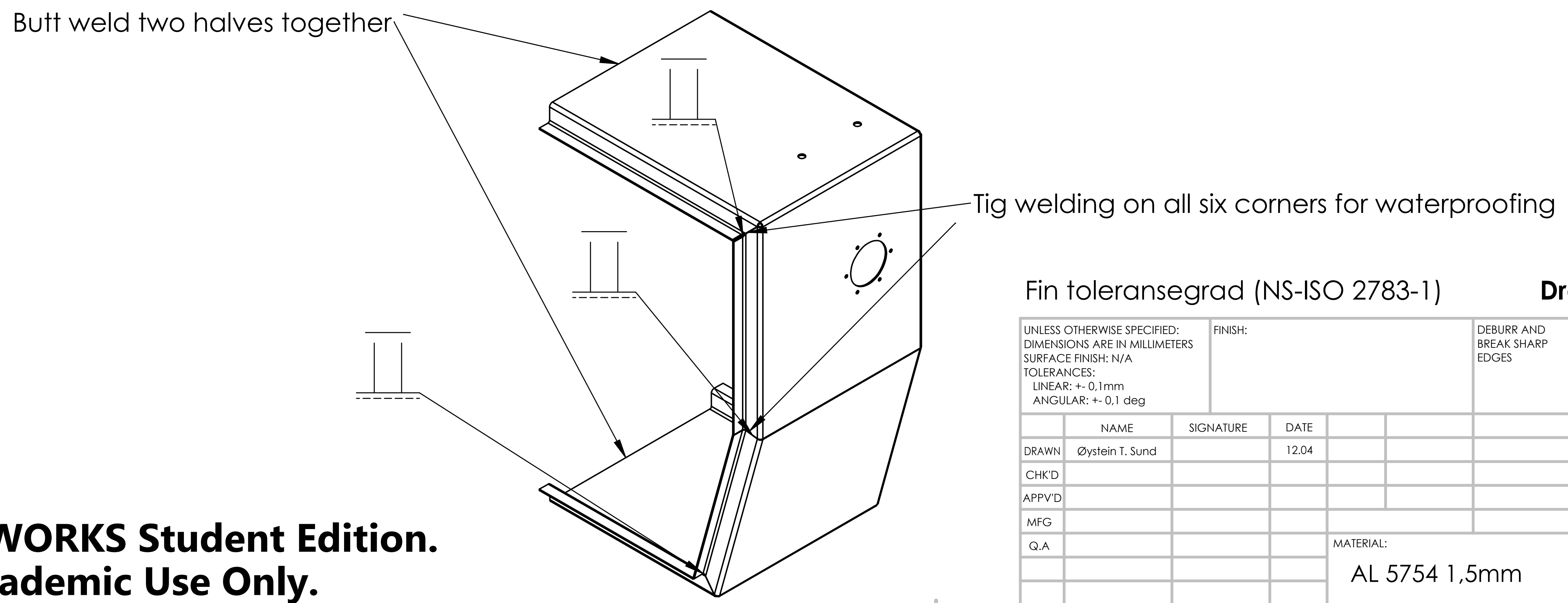


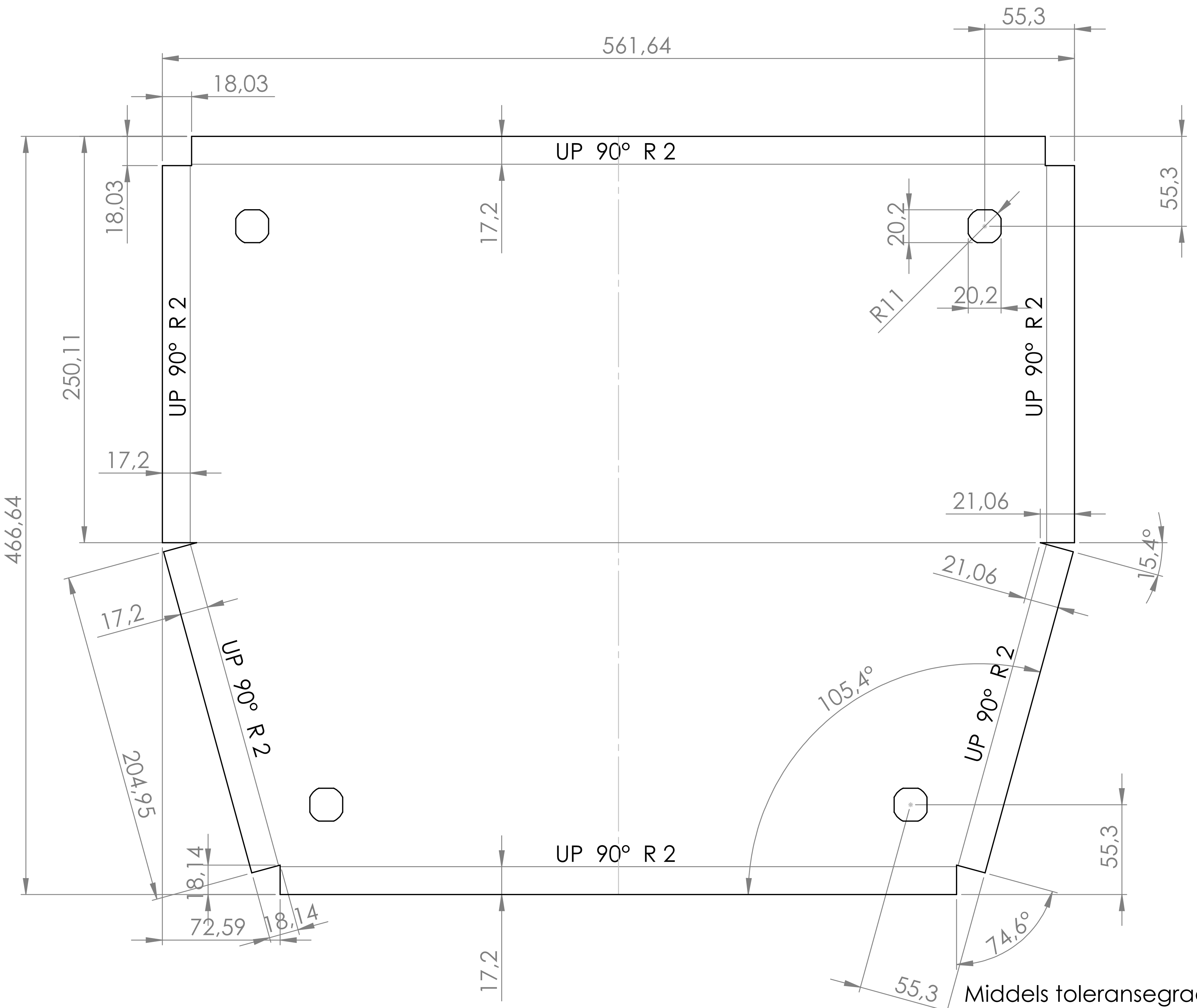


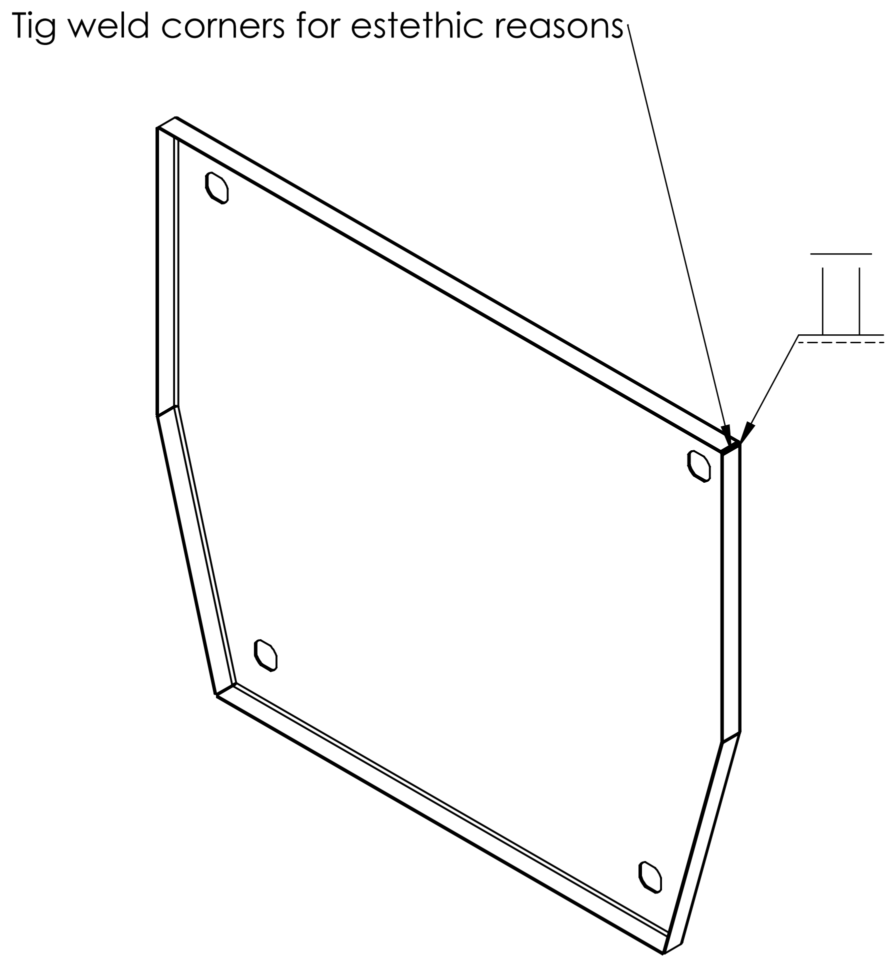
Fin toleransegrad (NS-ISO 2783-1)

Drawing also available as .dxf format

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: N/A TOLERANCES: LINEAR: +- 0,1mm ANGULAR: +- 0,1 deg	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A
	NAME	SIGNATURE	DATE	NMBU	
DRAWN	Øystein T. Sund		12.04	TITLE: **Thorvald II** RH EC box	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: AL 5754 1,5mm	DWG NO. EC1-04	A3
			WEIGHT:	SCALE:1:3	SHEET 1 OF 1

SOLIDWORKS Student Edition.
For Academic Use Only.



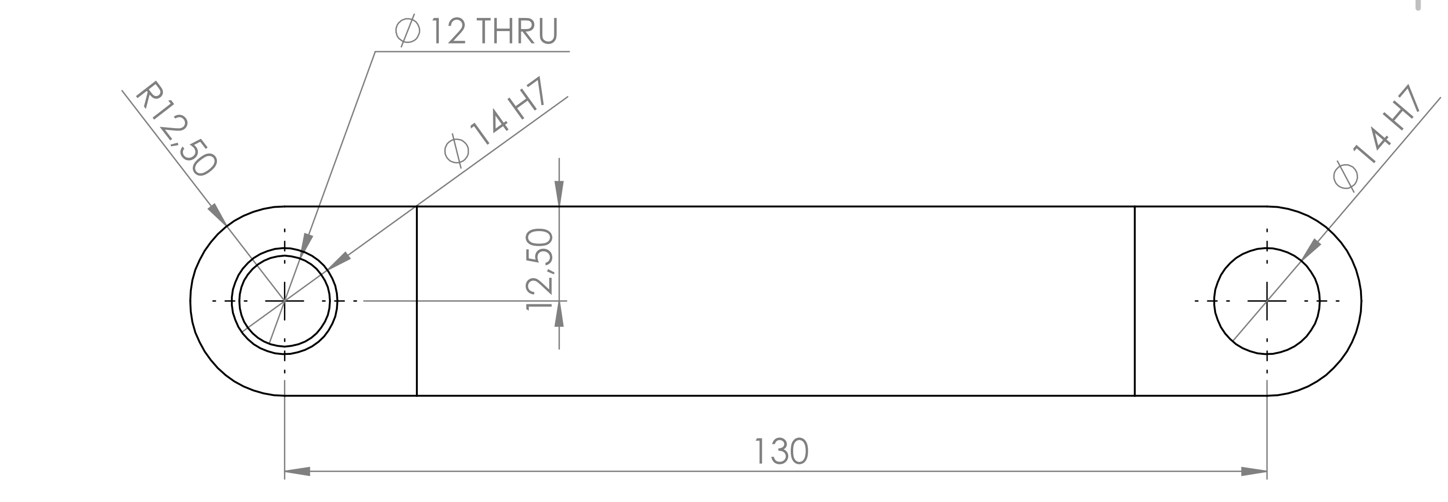


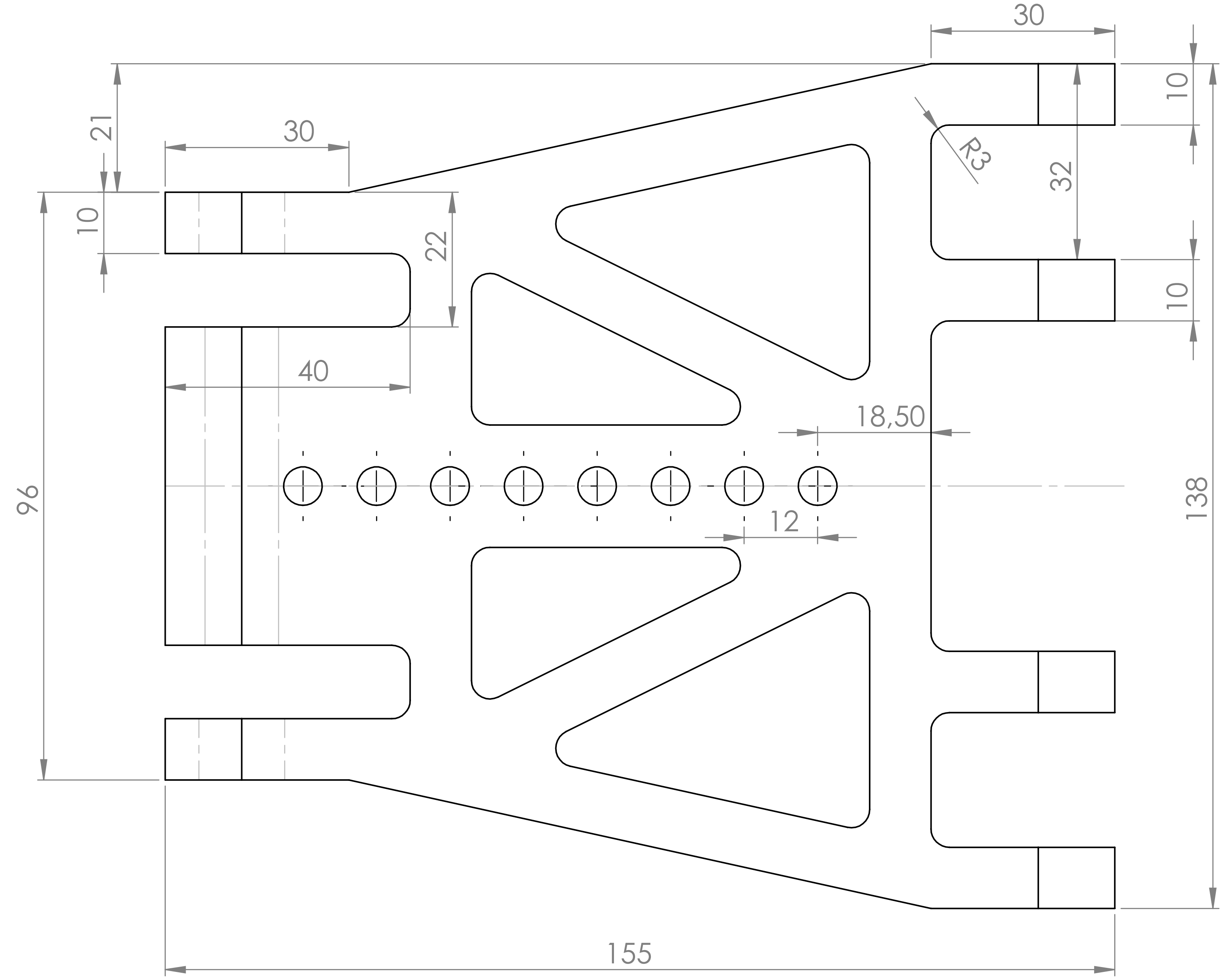
Middels toleransegrad (NS-ISO2768-1)

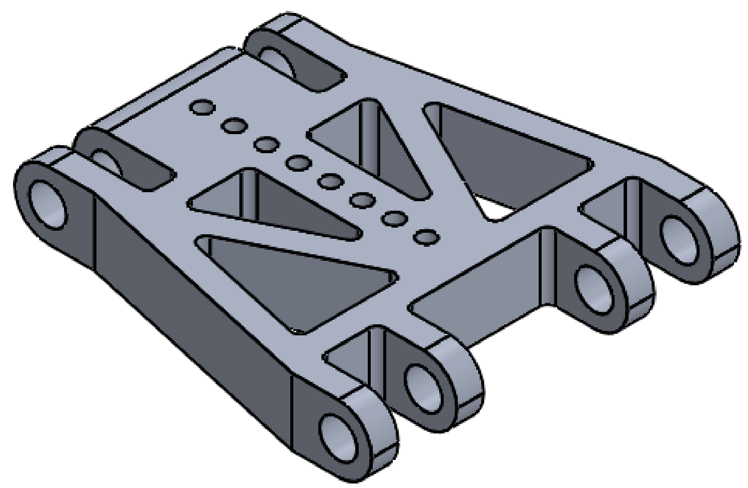
Drawing also available as .dxf format

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: N/A TOLERANCES: LINEAR: +- 0,1mm ANGULAR: +- 0,1 deg	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A
				NMBU	
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	Øystein T. Sund		12.04	**Thorvald II** ECbox Lid	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: AL 5754 1,5mm	DWG NO. EC1-05	A3
			WEIGHT:	SCALE:1:3	SHEET 1 OF 1

SOLIDWORKS Student Edition.
For Academic Use Only.



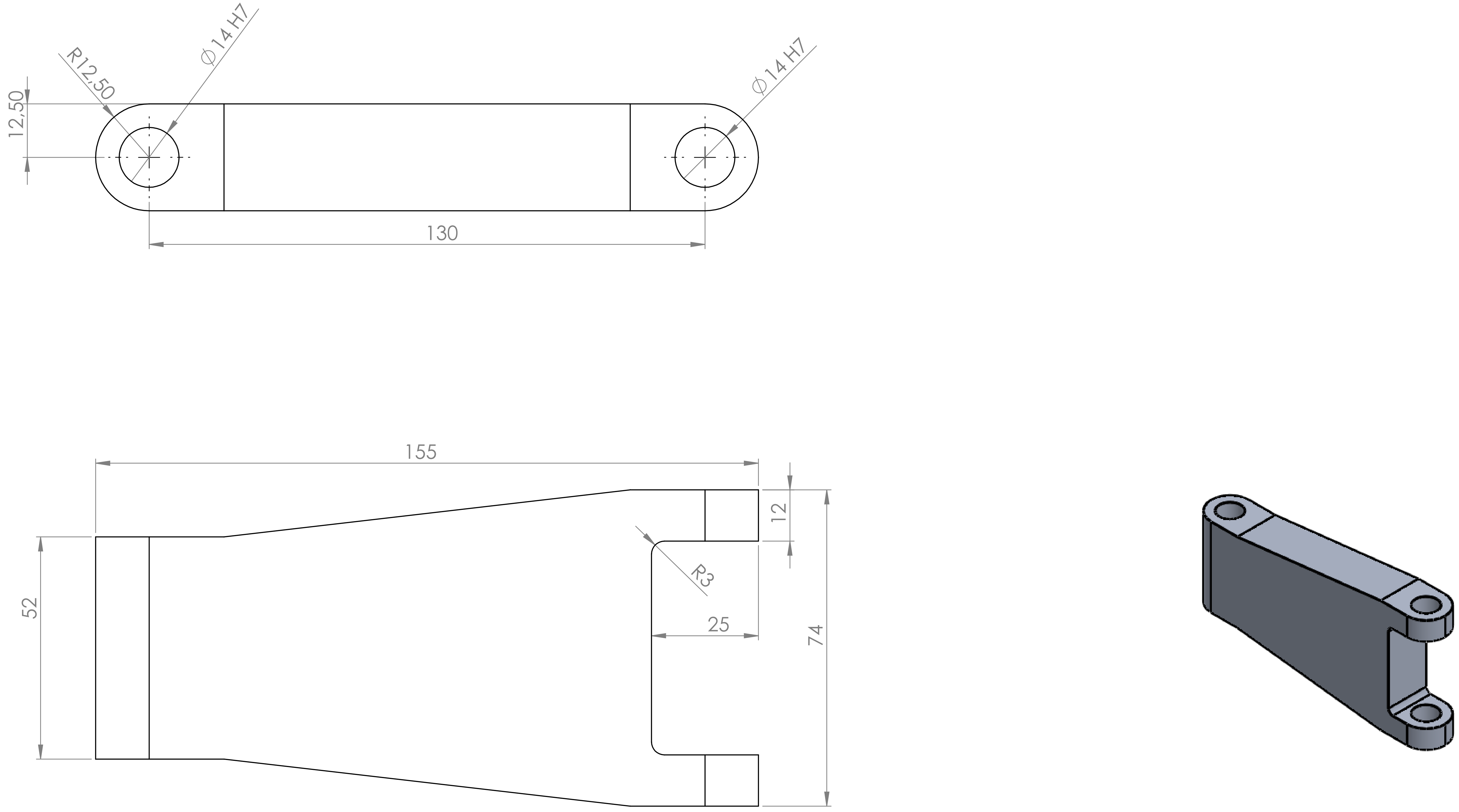




Also available as DXF format

Fin toleranseklasse på ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	1A
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	Øystein T. Sund			NMBU Heavy duty suspension arm	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: 6060T6 25mm	DWG NO. SA1-01	A3
			WEIGHT:	SCALE:1:1	SHEET 1 OF 1



Also available as DXF format

Middels toleranseklasse på ikke toleransesatte mal

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: 6060T6 25mm

WEIGHT:

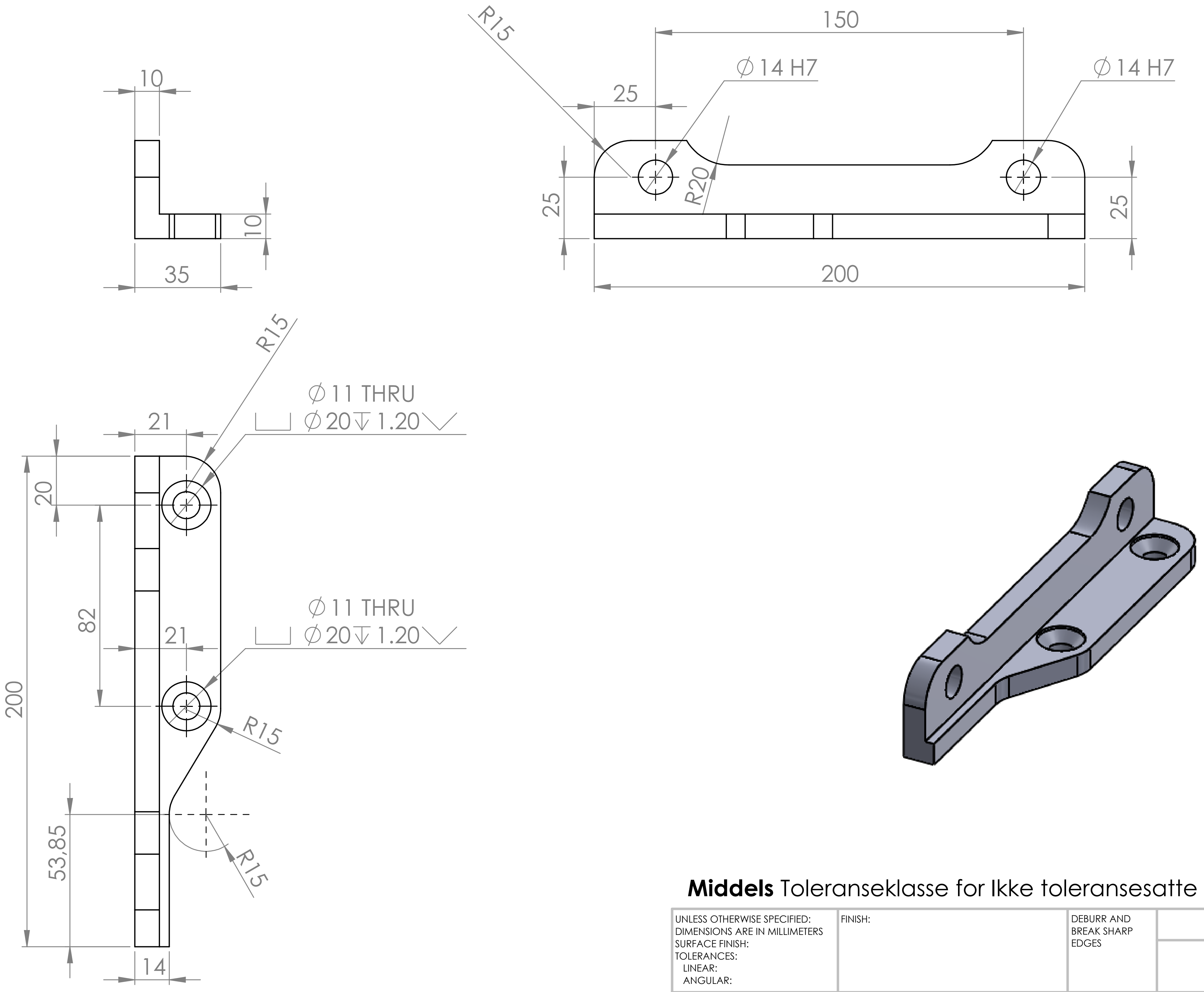
TITLE: NMBU Upper suspension arm

DWG NO. SA1-02

A3

SCALE:1:1

SHEET 1 OF 1



Middels Toleranseklasse for Ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T Sund		27.04
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

NMBU
LH Suspension L-Bracket

MATERIAL:
AL L-profil 100x100x10

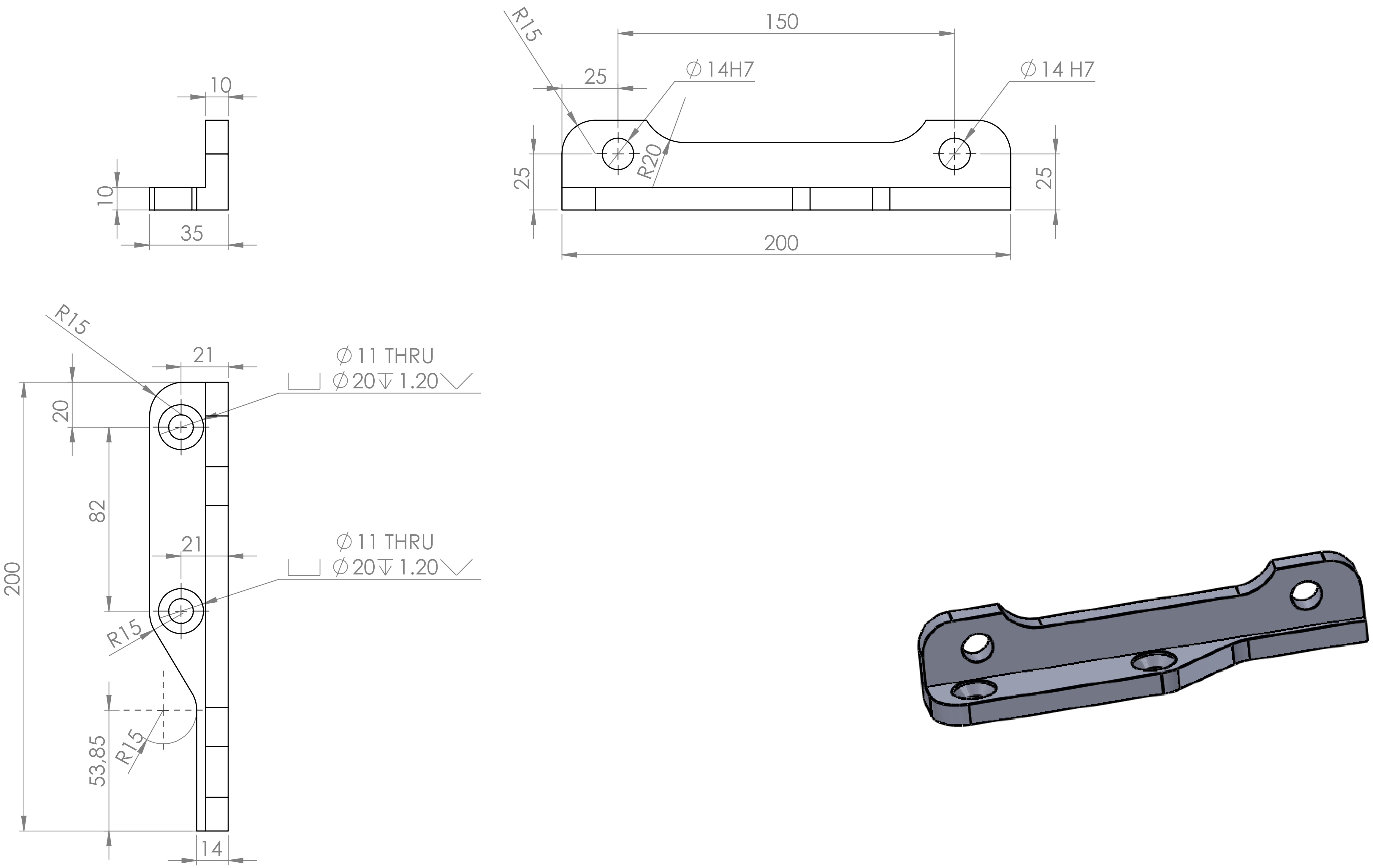
DWG NO.
SA1-03

A3

WEIGHT:

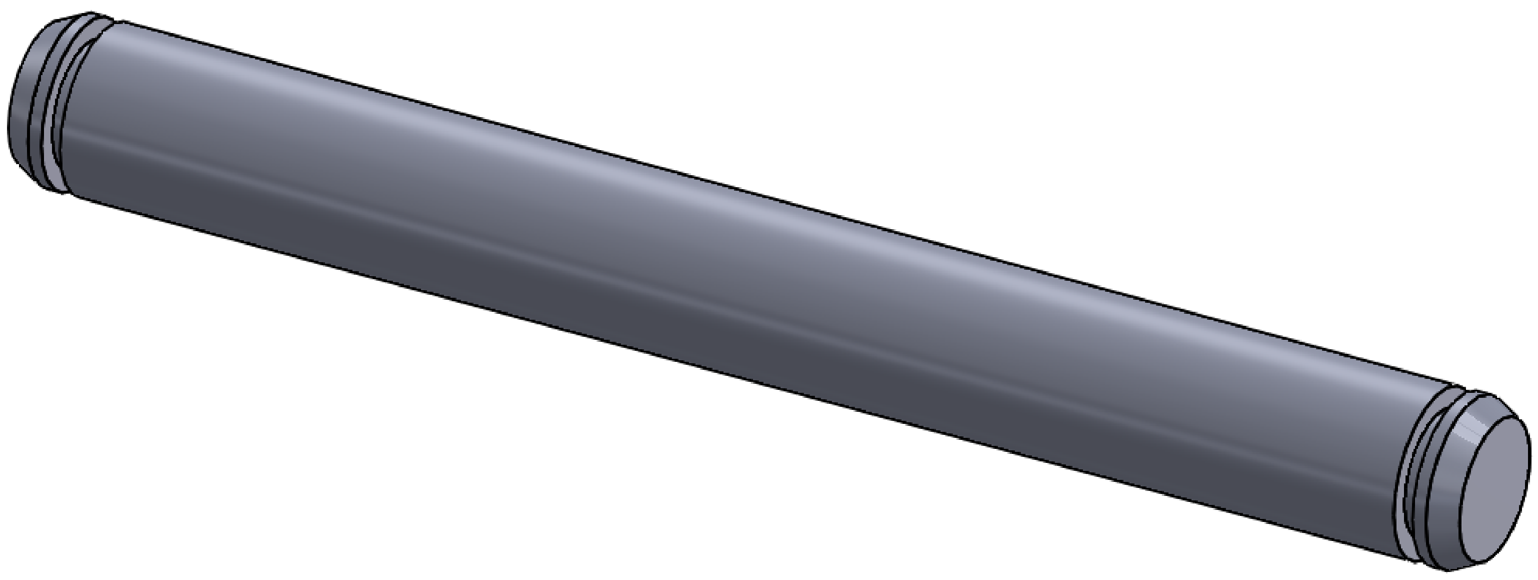
SCALE:1:2

SHEET 1 OF 1



Middels Toleranseklasse for ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A
	NAME	SIGNATURE	DATE		TITLE:	**NMBU** RH Suspension L-Bracket
DRAWN	Øystein T. Sund		27.04			
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. SA1-04	A3
				WEIGHT:	SCALE:1:2	SHEET 1 OF 1



Middels toleranseklasse for ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		27.04
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

NMBU

Lower Tower Hinge Pin

MATERIAL: RF 12mm AISI 304 h9

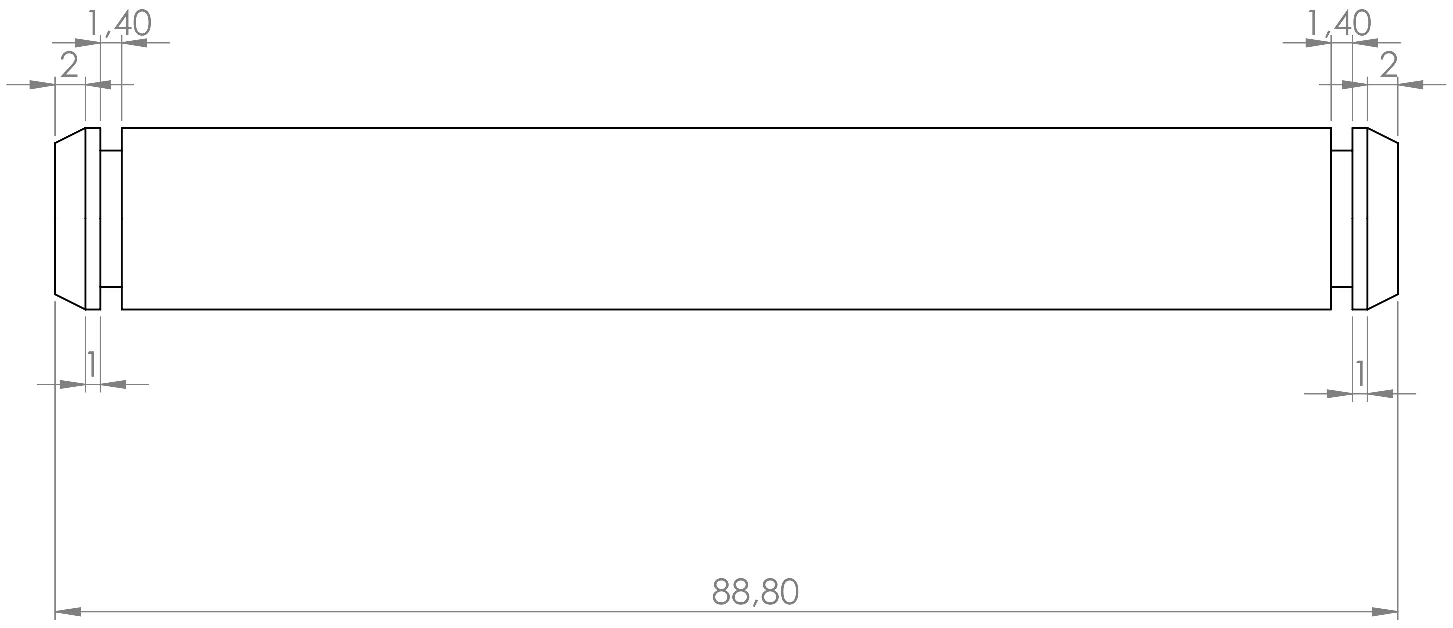
WEIGHT:

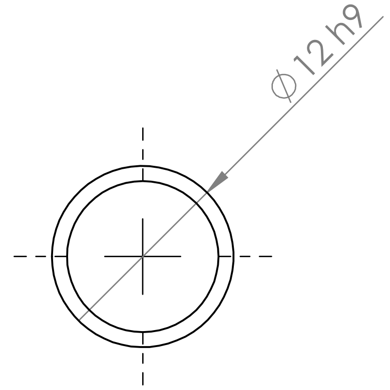
DWG NO. SA1-05

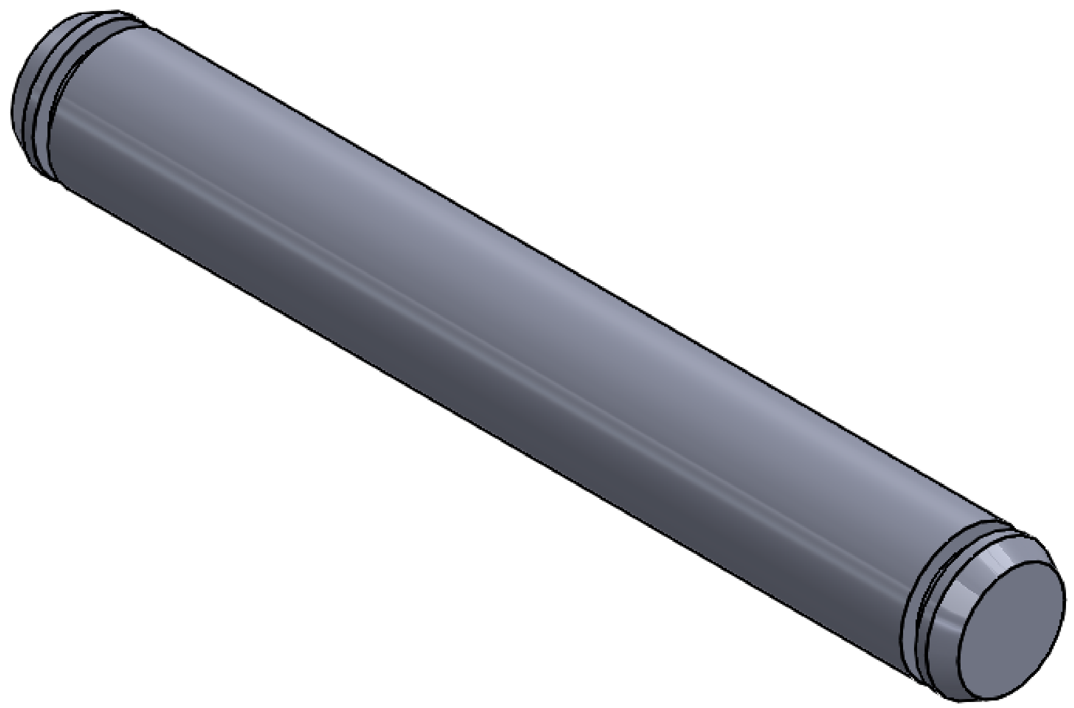
A3

SCALE:2:1

SHEET 1 OF 1







Middels toleranseklasse for ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE	
DRAWN	Øystein T Sund		27.04	
CHK'D				
APPV'D				
MFG				
Q.A				

MATERIAL: RF 12mm AISI304 h9

WEIGHT:

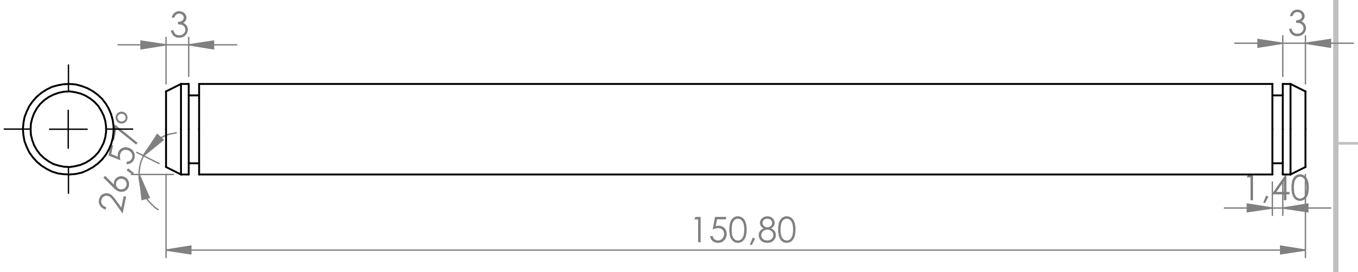
TITLE: **NMBU** Upper Tower Hinge Pin

DWG NO. SA1-06

A3

SCALE:2:1

SHEET 1 OF 1



Middels toleranseklasse på ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

NMBU

Lower Nacelle Hinge Pin

MATERIAL:

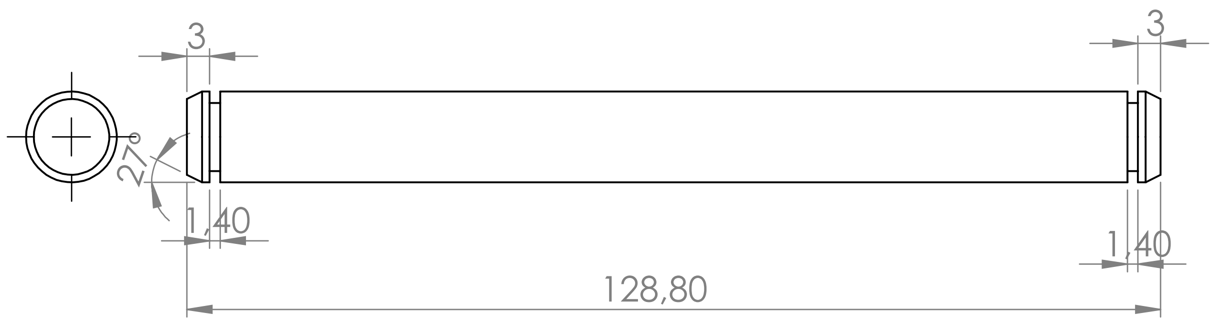
DWG NO. SA1-07

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



Middels toleranseklasse på ikke toleransesatte mål

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

NMBU

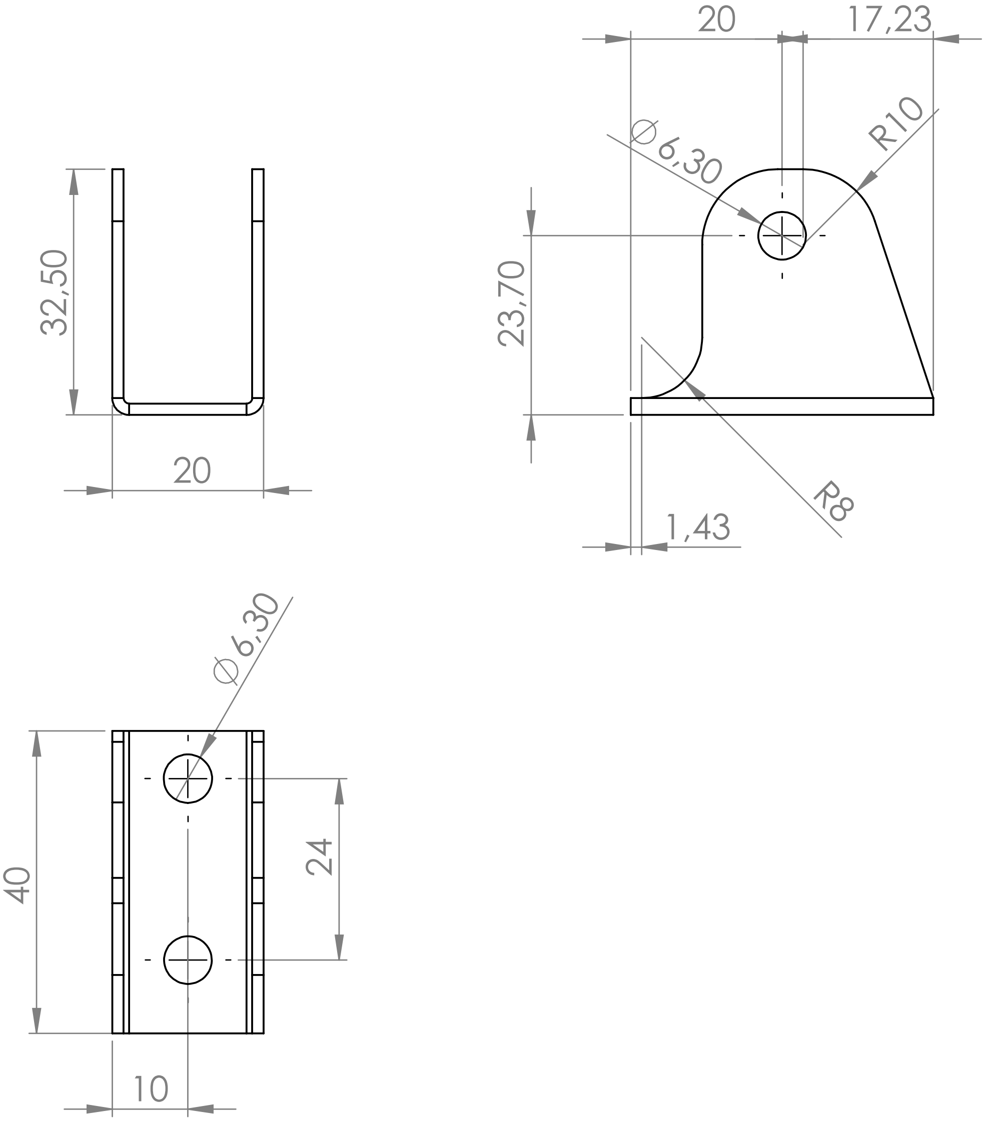
Upper Nacelle Hinge Pin

DWG NO. SA1-08

A4

SCALE:1:1

SHEET 1 OF 1



Middels Toleranseklasse på ikke toleransesatte mål (NS-ISO2768-1)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

NMBU

Lower damper hinge

MATERIAL: S235 Rectangular tube 40x20

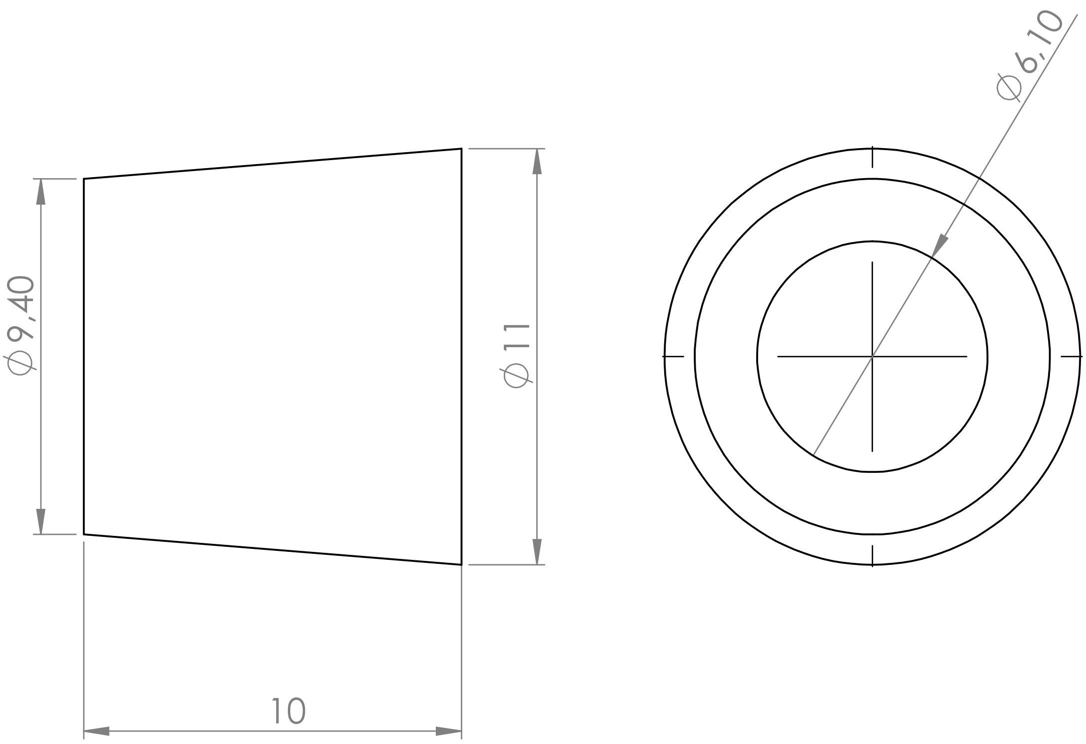
DWG NO. DA1-01

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



FIN Toleranseklasse på ikke toleransesatte mål (NS-ISO2768-1)

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

NMBU
Damper Bushing

MATERIAL:
Aluminum 6000-series

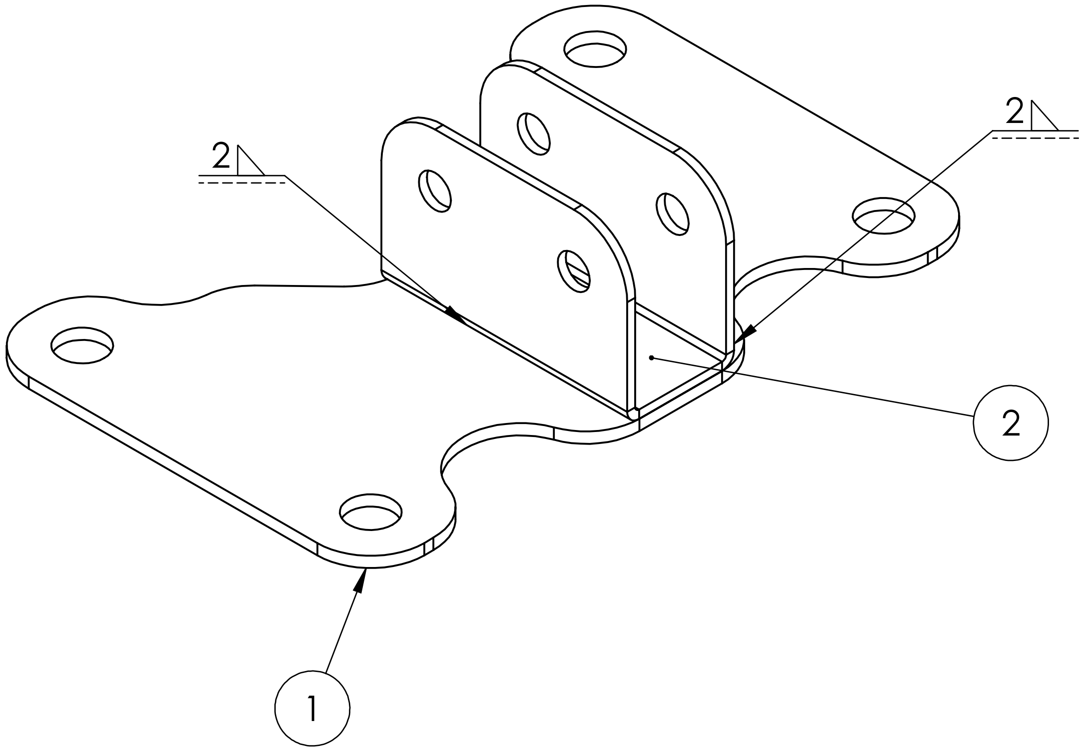
DWG NO.
DA01-02

A4

WEIGHT:

SCALE:5:1

SHEET 1 OF 1



QTY.	ITEM NO.	PART NUMBER	DWG No.
1	2	Top suspension hinge bracket	TD1-02
1	1	Top damper hinge base	TD1-01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

NMBU

Top Damper Hinge

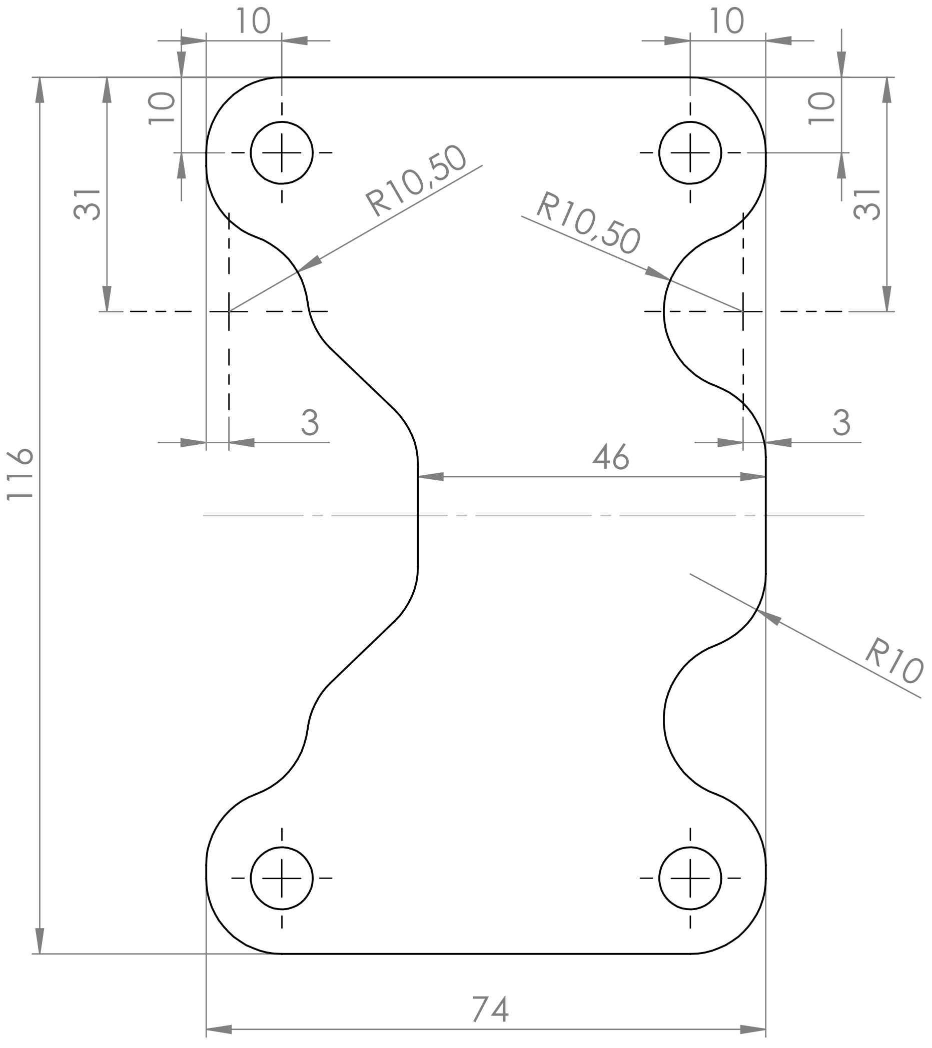
DWG NO.

TD1-00

A4

SCALE:1:1

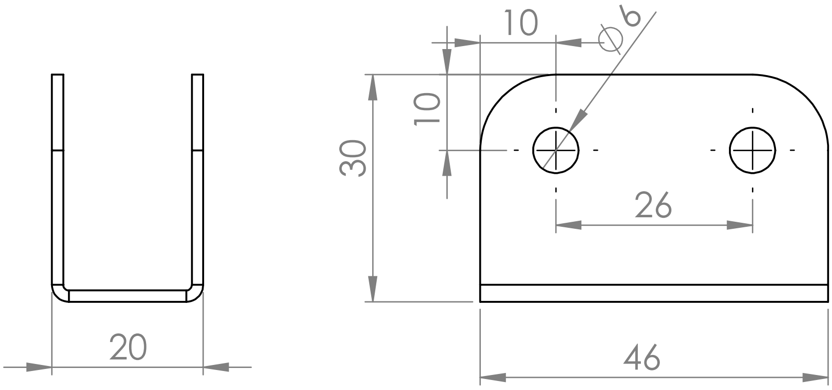
SHEET 1 OF 1



Drawing also available as .DXF format

Middels Toleranseklasse på ikke toleransesatte mål (NS-ISO2768-1)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	1A
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN	Øystein T. Sund		01.05	NMBU Top damper hinge base		
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: KV. PL DC01AM 2mm	DWG NO. DT1-01	A4
				WEIGHT:	SCALE:1:1	SHEET 1 OF 1



Middels Toleranseklasse på ikke toleransesatte mål (NS-ISO2768-1)

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 1A

	NAME	SIGNATURE	DATE
DRAWN	Øystein T. Sund		01.05
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

NMBU

Top suspension hinge bracket

MATERIAL:
S235 Rectangular tube 40x20

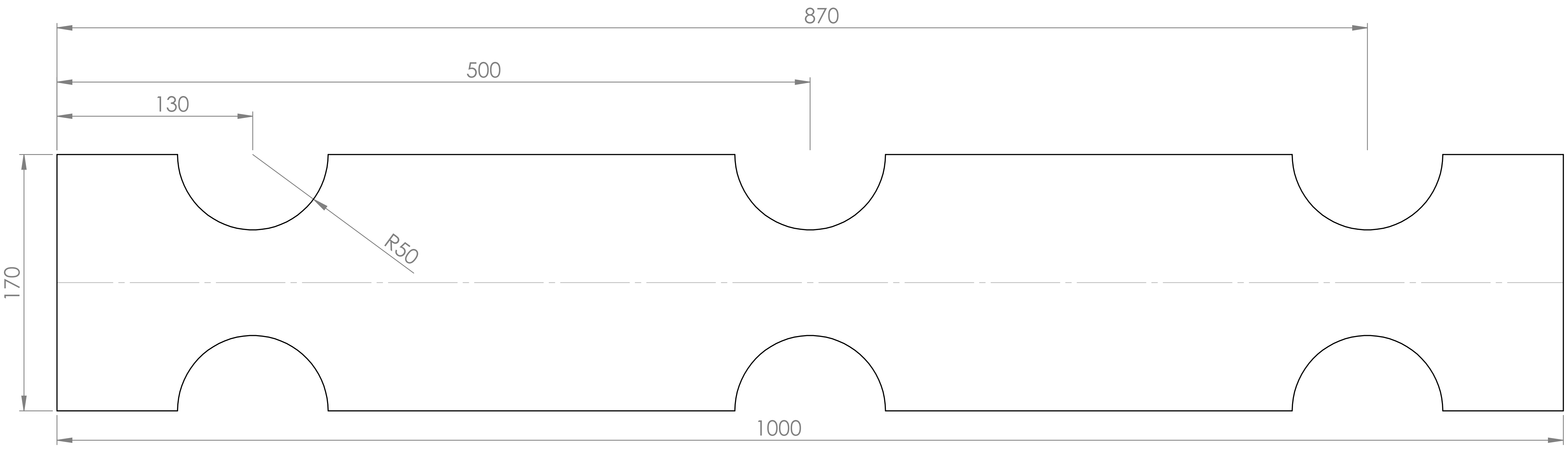
DWG NO.
DT1-02

A4

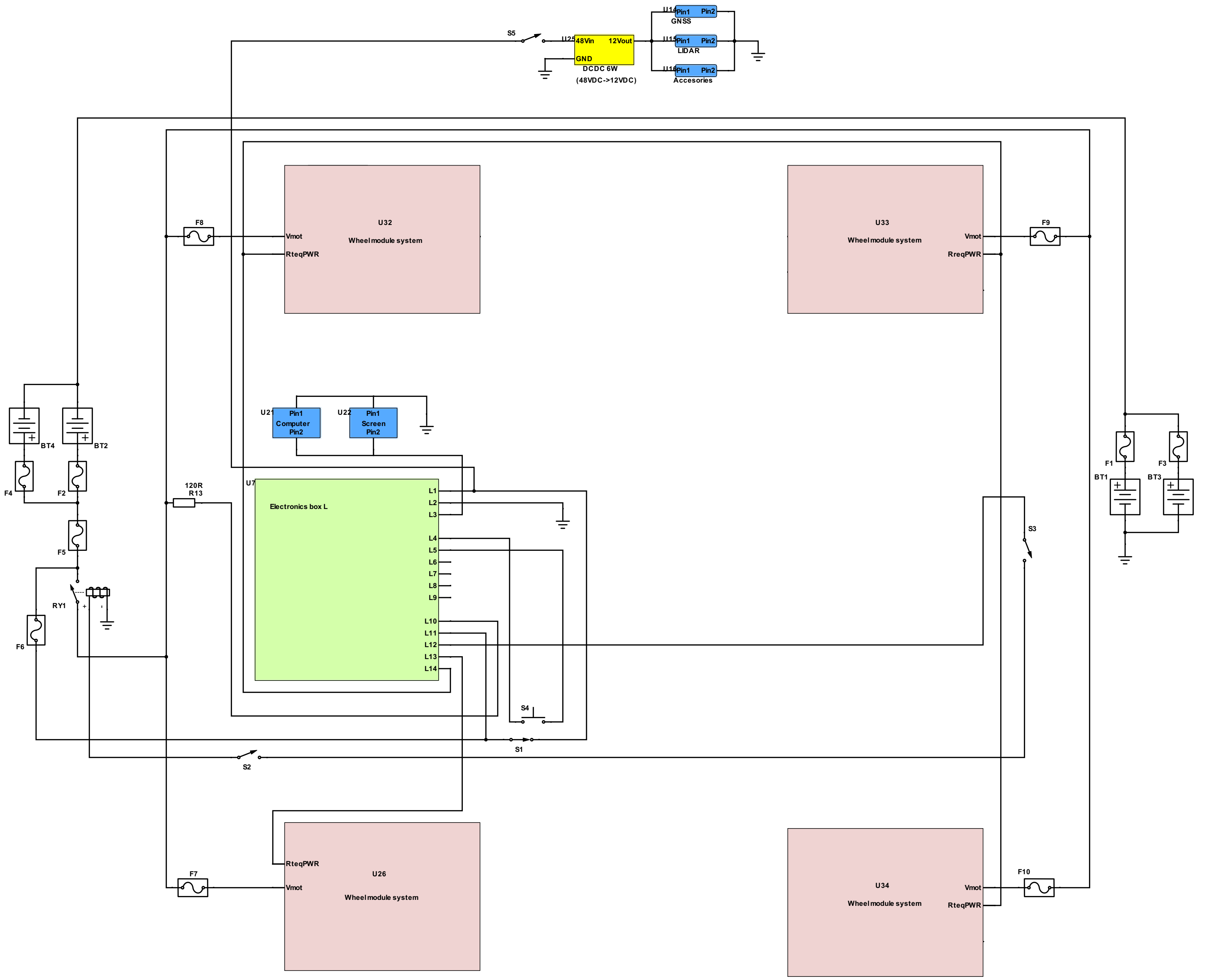
WEIGHT:

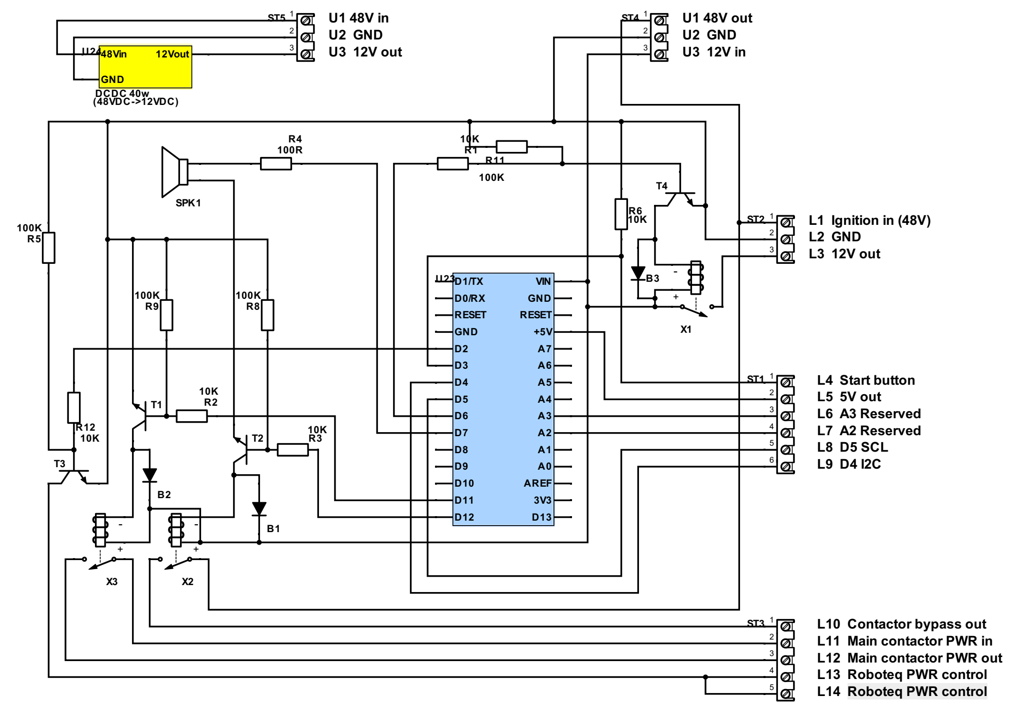
SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	1A
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN	Øystein T. Sund		01.05	**NMBU** Front plate simple		
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: 5050 T6 1,5mm	DWG NO. TH2-01	A3
				WEIGHT:	SCALE:1:3	SHEET 1 OF 1


S5
U25 48Vin 12Vout GND
DCDC 6W
(48VDC->12VDC)
U14 Pin1 Pin2 GNSS
U15 Pin1 Pin2 LIDAR
U16 Pin1 Pin2 Accesories
F8
U32 Vmot RteqPWR Wheelmodule system
U33 Vmot RreqPWR Wheelmodule system
F9
U21 Pin1 Computer Pin2
U22 Pin1 Screen Pin2
BT4
BT2
F4
F2
F5
RY1
F6
120R R13
U7 Electronics box L
L1 L2 L3 L4 L5 L6 L7 L8 L9 L10 L11 L12 L13 L14
S4
S1
S2
S3
F1 F3
BT1 BT3
F7
U26 RteqPWR Vmot Wheelmodule system
U34 Vmot RteqPWR Wheelmodule system
F10


ST5
U1 48V in
U2 GND
U3 12V out
U2 48Vin 12Vout GND
DCDC 40w
(48VDC->12VDC)
ST4
U1 48V out
U2 GND
U3 12V in
R4 100R
SPK1
10K R1
R11 100K
T4
R6 10K
B3
X1
ST2
L1 Ignition in (48V)
L2 GND
L3 12V out
100K R5
100K R9
100K R8
U23 D1/TX D0/RX RESET GND D2 D3 D4 D5 D6 D7 D8 D9 D10 D11 D12
VIN GND RESET +5V A7 A6 A5 A4 A3 A2 A1 A0 AREF 3V3 D13
T1
10K R2
T2
10K R3
R12 10K
T3
B2
B1
X3
X2
ST1
L4 Start button
L5 5V out
L6 A3 Reserved
L7 A2 Reserved
L8 D5 SCL
L9 D4 I2C
ST3
L10 Contactor bypass out
L11 Main contactor PWR in
L12 Main contactor PWR out
L13 Roboteq PWR control
L14 Roboteq PWR control

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Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

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NO-1432 Ås
Norway