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CHASSIS FRAME DESIGN OF A MOBILE PLATFORM EQUIPPED WITH ROBOTIC ARMS

Examiners: Professor Heikki Handroos
Dr, Ming Li

ABSTRACT

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Chassis frame design of a mobile platform equipped with robotic arms.

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The overall objective of the thesis is to design a robot chassis frame which is a bearing structure of a vehicle supporting all mechanical components and providing structure and stability. Various techniques and scientific principles were used to design a chassis frame. Design principles were applied throughout the process. By using Solid-Works software, virtual models was made for chassis frame.

Chassis frame of overall dimension 1597* 800*950 mm^3 was designed. Center of mass lies on 1/3 of the length from front wheel at height 338mm in the symmetry plane. Overall weight of the chassis frame is 80.12kg. Manufacturing drawing is also provided. Additionally, structural analysis was done in FEMAP which gives the busting result for chassis design by taking into consideration stress and deflection on different kind of loading resembling real life case. On the basis of simulated result, selected material was verified.

Resulting design is expected to perform its intended function without failure. As a suggestion for further research, additional fatigue analysis and proper dynamic analysis can be conducted to make the study more robust.

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Thesis writing has been both difficult and enjoyable process. Particularly, when the results derived were according to expectations it was enjoyable and fulfilling. However, there were also minor frustrating bumps along the way when I was stuck at particular problems. This is perhaps expected in any research process.

I would like to acknowledge the help of few particular people who helped me to overcome those frustrating bumps as I mentioned earlier. Specially, I would like to acknowledge the guidance and help given by Professor Heikki Handroos and Dr. Ming Li. Juha Koivisto was also immensely helpful during the process in providing valuable guidance related to technical drawings and other lab arrangements. Since, this thesis is primarily the result from a project of over 6 months, I would also like to acknowledge the help and support provided by all project members, especially Hamid Roozbahani who acted as our project manager.

Overall I would like to acknowledge immense love and encouragement provided by my family members: my parents, my elder brother and my sister- in- law. Without my brother's suggestions and loving support of my sister-in-law, this thesis would not have been complete.

Sameer kunwor

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LIST OF SYMBOLS AND ABBREVIATION

φ	Angle of Twist [◦]
σ_{max}	Maximum Stress [MPa]
ν_d, ν_p,	Deflection [mm]
b	Width of beam [mm]
E	Young's modulus [MPa]
F	Total robot gross weight [N]
F_{FT}	Total Force in front tire [N]
F_{RT}	Total Force in front tire [N]
F_{1V}, F_{2V}	Force in each front tire [N]
F_{3V}, F_{3V}	Force in each rear tire [N]
h	Height of the beam [mm]
K_T	Torsional stiffness [Nmm/◦]
L	base width of the robot, [mm.]
M_{FT}	Moment from Front tyre [Nmm]
M_{RT}	Moment from Rear Tyre [Nmm]
S_e	Elastic limit [MPa]
S_y	Yield strength [MPa]
T	Torque [Nmm]
I_x	Moment of inertia [mm^3]
x	Distance [mm]
y	the perpendicular distance from neutral axis in beam [mm]
y_{max}	Maximum deflection [mm]
CAD	Computer Aided Design
DFA	Design for Assembly
FEA	Finite Element Analysis
GRW	Gross robot weight [N]
TW	Track width [mm]
VM system	Vehicle-manipulator system
WB	Wheel base [mm]

1 INTRODUCTION

The chassis refers to the backbone structure of a vehicle. It supports the body and other mechanical components of a vehicle during movement. The chassis should also facilitate the assembling process so that other mechanical components can be mounted on this chassis frame. (Genta et al., 2014, p. 15.) By definition then, being a backbone structure; it should be strong, robust, lightweight and with the ability to withstand heavy loads.

1.1 Background

Chassis has similar meaning in the design of a robot. In the context of the robot, chassis supports, bears the load of different mechanical components even under heavy performance requirements and lead to stability of the robot. Since, other mechanical components are mounted on the chassis frame, the chassis should be designed in such a way that it leads to overall stability of the robot, as with each addition of mechanical components the center of gravity of the structure keep on shifting. Therefore, chassis is a critical component of a robot and the chassis design should focus on stability allowing for proper places for different parts of the robot.

1.2 The objectives of the thesis

The objective of this thesis is to develop the Computer Aided Design model of the chassis, produce the manufacturing drawings and verify the deformation, stability and the loading capacity of the robot chassis frame and eventually manufacture the physical body frame. It is also necessary in the chassis design to count the specifications imposed by the functions of the mobile robot which includes two UR10 robotic arms, landing space for quadcopter and drive modular system containing 4 Mecannum wheels. These specifications will be clarified during the design phase of robot chassis frame. Since this thesis is only focused on the structural design of the chassis frame, the actual description of controlling mechanism for the robotic arm and Omni wheel is beyond the scope of this thesis. During the project, other project members were involved in specifically designing the controlling mechanism of the tele operated mobile robot.

The vital part of chassis design also includes the selection of material to be used in the structure. Additionally, both static and dynamic finite element analysis should also be conducted. The idea is also to produce a manufacturing drawing for the robot chassis frame which can then be used for the manufacturing process. In this thesis, chassis frame is designed and developed by using appropriate manufacturing and mechanical principles by using commercially available finite element software. Before the development of the final chassis frame several project meetings also took place in which design parameters and material specification were finalized. At the end, fully functional manufacturing drawing of a robot chassis frame are produced. Further steps would include undertaking of electrical and other control tests for the chassis frame.

1.3 Summary of content

The objective of this thesis is to design robot chassis frame considering appropriate design and other mechanical principles. Chapter 2 is concerned with the literature review. Literature review mainly deals with different types of chassis frames, different components required to build a robot chassis and the mechanical principles behind the design and construction of chassis including the finite element method. Chapter 3 is concerned with the actual design of the robot chassis. It starts with the discussion of general design principles and procedures and the application of these design principles in the construction of robot chassis frame. In this chapter, designed chassis frame is illustrated with the application of relevant mechanical principles and the resulting manufacturing drawings are provided in the appendixes. Chapter 4 deals with the analysis and verification of chassis frame design. This includes for instance the application of finite element method. The strength of the material is verified along with the overall design of the robot chassis frame compared with the conventional standards. Chapter 5 deals with the presentation of results after designing the robot chassis frame and discussion of the design procedures and project in general. Chapter 6 concludes the thesis highlighting the major findings and some suggestions for further development.

2 BACKGROUND AND LITERATURE SURVEY

The purpose of this chapter is to review previous researches related to chassis design and to identify key requirements for chassis design. The components required to build a mobile robot in general are also discussed in this section. Overall the objective of the literature survey is to identify the key mechanical principles and components that will facilitate the design of chassis frame.

2.1 Designing mobile robot with robotic arms

Although design process is a creative activity, several rational decision making is involved throughout the design process. Mechanical system parameters should be satisfied where general configuration, performance specification and detailed definition should conform to the design requirements. Design of mobile-manipulators is even more difficult because they are designed to operate in dangerous environments.

The design of control mechanisms for mobile manipulators is also challenging. For example, if tele operations are used as controlling mechanism, mobile manipulators must be controlled by several operators at once including the one to control the mobile base and others to control different manipulators. Since several operators must be able to communicate with each other, design process can be at once complex, expensive and slow in order to derive the optimum solution. The alternative way would be to develop autonomous system by adding sensors which enables the environmental data to be read. This information then can be used by the mobile manipulator to determine appropriate movement. (Steven , 2009, p. 7.)

Recent researches also suggest the possibilities of simplifying the control of redundant mobile manipulators by the use of kinematic singularities of the manipulators. If this were in fact possible, it would be possible to control the system via one operator. This could also enable fast reactivity to environmental stimulus by the robot. Additionally, this would increase the possibility for mobile manipulators to be practically used in the workplace particularly when it is hazardous for human workers. The results however are not yet concrete from these researches. (Steven , 2009, p. 8.)

2.2 Need for a Test-Bed

This section highlights the need for a platform as a test bed where other constituent parts are mounted. As the overall goal of this project is to design a tele operated mobile robot, it also makes it necessary to design a platform. It is in this mobile platform that other individual parts and the overall system is mounted and connected. The primary focus of this thesis is to design the chassis frame which acts as a skeleton in the completed mobile robot platform.

In this chassis frame, vital components of the robot such as UR10 robotic arm and drive modular are connected. When the robot is in use, motion of both the robotic arm and the drive modular creates torque, and it is vital to design a chassis frame that takes it into consideration. Additionally, the purpose of the project is also to design a system where mobile robot can be controlled by input from a joystick. Since, input from a joystick can also be unbalanced in many circumstances, an appropriate chassis frame design can limit the adverse effects.

2.3 Vehicle-manipulator system

According to From, Gravdahl & Pettersen (2014, p. 6.), The Vehicle-manipulator (VM system) can be define as "a robot that is intended to operate with dexterity in a workspace larger than that of a fixed –base manipulator." VM System is made up of two primary components: which includes base comprising of actuation allowing it to move flexibly in its environment and other manipulator arms that are then attached to its base. Robot using vehicle manipulator system perform much better in larger workspaces in comparison to a robot which uses fixed base manipulator. (From et al., p. 6.)

It is the base of the VM systems that provides it with the ability to move over geographical spaces. This base can both be a normal vehicle or another robot which provides it the ability to move over confined spaces. All of these systems, both normal and robotic device are referred to as VM systems. In other words, vehicle can be any kind of base where the robotic arm can be mounted, as long as they move with ease in confined spaces and are able to work in bigger spaces. (From et al., 2014, p. 6.)

The types of the manipulator arms that are mounted in the VM systems can also be different. For example, sometimes they can be of the general type which are used in industrial settings or on the other hand, thin and movable in nature. The latter type can be folded into the structure when it is not in use. Overall, whichever robotic arm is mounted it should be able to move freely to complete the required tasks. From this discussion, it is quite evident that the nature and design of manipulator arm is largely dependent upon the environment for which it is designed. (From et al., 2014, p. 6.)

2.4 Chassis

Although, chassis is a French word, its dictionary meaning in English defines it as an assembly of structural elements of the vehicle or the assemblage and mechanical element that can provide motion in a vehicle. For example, according to Heissing & Erosy, (2011, p. 1), chassis can be define as "suspended steel frame, which carries the motor and all accessories necessary for regular operation". When the vehicle systems are considered, chassis is only a subassembly component which should be available at different stages of the assembling process. However, increasingly if the whole system is considered, it is no longer possible to separate chassis as a separate entity from the car, for example, or to consider its structural function as distinct. It can only be visible as darkened elements of the phantom view.

Although, there is no clear cut definition of chassis, the marketing definition of chassis is helpful. In marketing, as mentioned in Wijckmans & Tuytschaever (2011, p. 320.) "half-finished product consisting of the frame components, the driver station and the power train [transmission, driveshaft, axles and motor] which is eventually used for constructing a finished vehicle". In more general terms, chassis is quite simply the part of the vehicle system. Figure 1 shows different sub components of chassis.

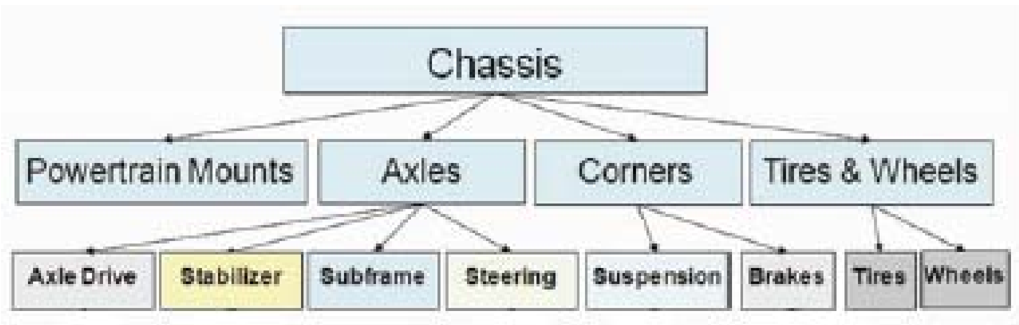


Figure 1. Component of modern chassis system (Heissing et al., 2011, p. 1).

If we were to consider all of the components shown in figure 1, it is suggested that the added weight of all the components will amount to one-fifth of the total weight and around 15 % of total production costs while manufacturing a mid-range, general purpose vehicle. (Heissing et al., 2011, p. 1.)The chassis as a whole is the defining characteristic of a motor vehicle in terms of performance, handling, safety and comfort than when other components are considered. Since all machines must be optimized at the systemic level, including motor vehicles, the design of a chassis is a critical element in the overall design process. (Genta & Lorenzo, 2009, p. 103.) The defining properties to be considered in chassis design are explained in this section step by step.

2.4.1 Symmetry considerations

Symmetry is one of the most important consideration in chassis design. Most of the engineering design, for instance, have bilateral symmetry as it is also common in nature. In many cases, the symmetry considerations can be simply aesthetic i.e. a symmetric object is beautiful. Dynamic analysis and modelling of a system is also easier to conduct when it is a symmetric plane by utilizing uncoupled form of equations. (Genta et al., 2009, p. 103.)

In a symmetrical chassis frame, the total weight is evenly distributed in a plane. As discussed beforehand, however, the actual distribution of load in mechanical systems is not always symmetrical. Still, the distance of the center of the mass from the symmetry plane is small. (Genta et al., 2009, p. 105.) This is going to help in the effective design of chassis.

2.4.2 Reference frames

The study of the motion of a vehicle always has a frame of reference. There are generally two categories of reference frames: earth fixed axis systems and vehicle axis systems. (Genta et al., 2009, p. 106.) Figure 2 shows the differences between these two reference frames. These are further elaborated in following sections.

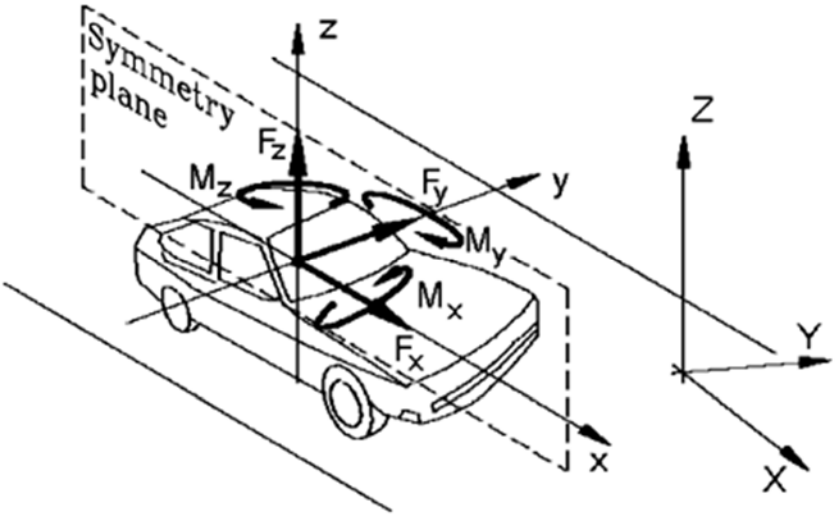


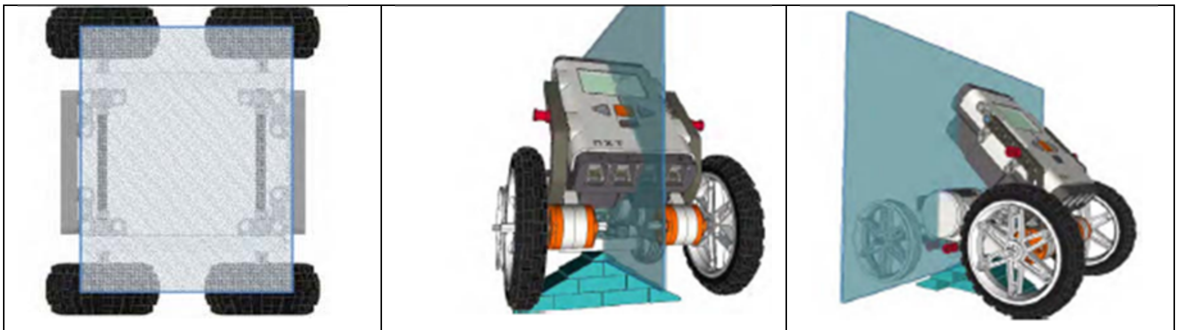
Figure 2. Reference frame, force and moment in dynamic study of the vehicles (Genta et al., 2009, p. 107).

Earth-fixed axis system XYZ: It is also sometimes referred to as the inertial frame, although if movement along the earth is considered it is not always so. When studying motor vehicle dynamics, however, this effect is negligible. The simple way to understand this axis system is to envision axes X and Y as positioned in the horizontal plane and the axis Z as perpendicular to the road. (Genta et al., 2009, p. 107.)

Vehicle axis system XYZ: This, in contrast, can be thought of as a frame of reference affixed to the moving vehicle's center of mass and moving in the same direction. In a vehicle with a symmetric plane, the center of mass lies in the same plane. X axis then is along the horizontal direction of the symmetry plane. The Z axis in the vehicle axis system is perpendicular to the X axis (pointing upwards). The Y axis is perpendicular to both other axis and turns towards the left points towards the left of the driver. When the vehicle does not lie in the symmetric plane, plane in the XZ direction lies along the vehicles straight motion considering the direction perpendicular to the road in the reference position of the vehicle. (Genta et al., 2009, p. 108.)

2.4.3 Position of the center of mass

One of the most important factor determining the behavior of a vehicle is the center of mass. Therefore, it is important to compute or assess it during the design stage or to determine it experimentally. This is because it is very important for a robot to be properly balanced so that it can perform consistently and repeatable manner while meeting its desired goals. The balance of the robot is ultimately dependent on the wheel base and center of gravity. If the center of gravity is close to the center of the wheel base, the robot is more balanced. Centre of mass is derived by taking the average of the masses from the reference point and is often used to mean the same thing as center of gravity. However, this can only be true in a uniformly distributed field of gravity. (Trobaugh, 2011, p. 25.) During the design phase considerable interest is placed in determining the center of mass in various operating conditions. Which is illustrate in figure 3.



(a) (b) (c)

Figure 3. (a) Wheel base of four-wheel (b) longitudinal balance plane (c) lateral balance plane (Trobaugh, 2011, pp. 25-26).

2.4.4 Mass distribution among the various bodies and moment of inertia

If multibody dynamics were to be considered, different bodies consisting of different nature of inertia should be taken into account. Vehicles for example has a rigid body where more bodies are added to wheel through axle with independent suspension mechanism. (Genta et al., 2009, p. 110.) Similarly, moment of inertia is also important to consider. It refers to rotational kinetics that mass plays in linear kinetics as a result of resistance of a body to changes in its motion. The moment of inertia in turn is dependent upon the distribution of mass around an axis of rotation which will obviously vary according to the axis chosen.

In any dynamic part, adding additional weight can reduce the machine's safety factor, allowable speed and payload capacity. If the kinematic acceleration are not reduced by slowing the vehicle's operation, added mass will increase the inertial loads in corresponding parts. As a result, while added mass may increase the strength of the part, the resultant increase in inertial force may outweigh the benefits so derived. (Norton, 2006, p. 4.)

2.4.5 Power train layout

Power train layout refers to the combination of gear, shaft, motor, coupler and other components. It is the mechanisms through which force is transmitted from motor to the wheel which causes the motion in a vehicle. Power train layout can be combined linearly, vertically as well as horizontally. When designing chassis, it is also necessary to consider power train layout because the internal force, torque and vibration caused by power train layout can affect the stiffness and durability of chassis.

2.5 Automotive chassis frame type

When choosing the type of chassis frame it is important to consider the material used because it is ultimately the bearing structure where other mechanical components, the body and payload are mounted. Similarly, the frame also provides support for assembling all other chassis components including the engine so it should be rationally organized so that it facilitates the fabrication process of the vehicle .There are basically four different types of chassis frame: ladder frame, backbone, space and monocoque types of chassis frame. Each of these are elaborated further in this section.

Ladder frame chassis consists of two longitudinal beam connected by multiple cross member. Generally this type of frame is simple, versatile, durable and cheap to manufacture. However, it also has negative qualities such as high center of mass, weak torsion and difficult to integrate. Figure 4 illustrates a ladder chassis frame. The most significant advantage of this frame is that it is adaptable and can compose large body of different shapes and types. When it is connected by a cross member it also has low torsional stiffness. (Happian-smith, 2001, p. 137.)

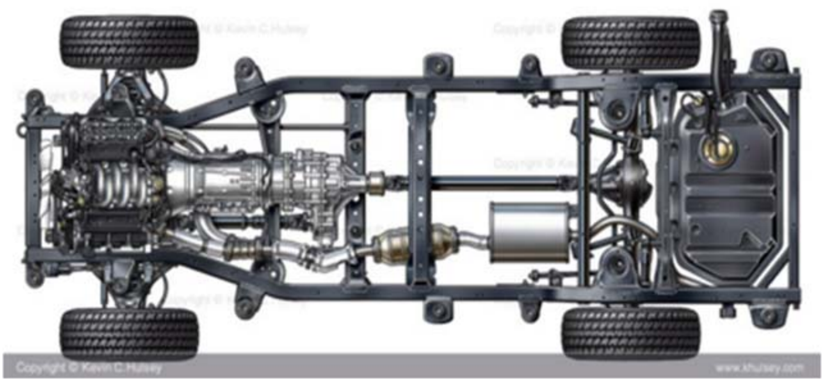


Figure 4. Ladder frame chassis (Hulsey, 2015).

Backbone chassis frame is a single, large, longitudinal structural beam which runs down the center of the vehicle with lateral splayed beams connecting the suspension. The main advantage of this type of chassis frame is that it has improved torsional stiffness. Bending as well torsional loads can be subjected on this type of chassis frame (Happian-smith, 2001). Figure 5 illustrates the backbone chassis frame.

Figure 5. Corgi lotus elan back bone chassis (Gray, 2008).

Space frame chassis is a complex structure that consists of many tubes joined together in triangulated format and it supports loads from suspension. It is generally light in weight and stiff. The chassis frame described earlier is a plane type of structure but the space frame has more depth which increases its bending strength and stiffness. In order to design space frame chassis, it is necessary to ensure that all of the planes are fully triangulated as these beams are loaded in tension or compression. (Happian-smith, 2001, p. 141.) Figure 6 illustrates this space frame chassis.

Figure 6. Space frame chassis (Nathan, 2014).

Monocoque, is a combination of Greek word mono meaning single and French word coque meaning shell effectively denoting monoshell. In a Monoshell construction, the load of the base structure is supported by external skin. In its design, panel's structure are used. This panel provides the strength for a given side. Geometrically this type of structure is very complicated even though it has numerous advantage such as lower weight, good torsion and bending load handling. (Happian-smith, 2001, p. 143.) Figure 7 illustrates the monocoque chassis frame for Jaguar XE model.

Figure 7. Jaguar XE monocoque chassis frame (Strauss, 2013).

2.6 Categories of factors affecting design considerations

Majority of engineering designs need to consider various factors in appropriate proportions. Although, factors affecting designs vary on a case by case basis, the major categories that need to be considered generally are highlighted in figure 8.

Major Categories of Design Considerations

Traditional Considerations
1. Materials
2. Geometry
3. Operating conditions
4. Cost
5. Availability
6. Producibility
7. Component life

Modern Considerations
1. Safety
2. Ecology
3. Quality of life

Miscellaneous Considerations
1. Reliability and maintainability
2. Ergonomics and aesthetics
3. Assembly and disassembly
4. Analysis

Figure 8. Categories for design consideration (Juvinall & Marshelk, 2008, p. 14).

The first step in designing machine components is to formulate the requirements precisely. A good formulation of a design problem should consider appropriate physical situation and a corresponding mathematical solution. However, mathematical representation of an actual physical situation is only an approximation. The following step should synthesize the structure, understand its interactions with the surrounding and draw visualizing diagrams. Thereafter, the problem should be analyzed by making appropriate assumptions while considering applicable natural laws, their relationships and other rules that relate the geometry to the behavior of the component. At the last stage, the reasonableness of the results should be verified. (Juvinall et al., 2011, p. 19.)

Most of the analysis directly or indirectly consider factors such as statics and dynamics, the mechanics of used materials, different formulas and conservation of mass principle. For engineering problems, it is also necessary to consider the physical characteristics of the materials used in designing components and how they relate to each other. (Juvinall et al., 2011, p. 19.) This can, for example, be analyzed through load analysis. Since structural components of a machine are load-carrying members, it is important to conduct analysis of loads. The resulting stress and deflection analysis will be incorrect if the value of loads used are incorrect. Without considering appropriate loads, the design of a mechanical component will not lead to satisfactory results. (Juvinall et al., 2011, p. 45.) After external loads applied to a component is determined, it is then necessary to determine the resulting stresses. In the context of this thesis, the resulting stress is primarily body stress which exists within a member as a whole and is different from contact stress in localized regions when external loads are applied. (Juvinall et al., 2011, p. 131.)

2.7 Principles behind selection of material and analysis of material properties

In designing a machine component, the type of materials selected and the fabrication process are important considerations. For the material selection, strength and rigidity of the material and primary considerations. It is also necessary to consider the reliability and durability of component parts when they are made from other materials. In figure 9, the stress-strain curve for hotrolled 1020 steel is presented as an example to illustrate relationships between different material properties.

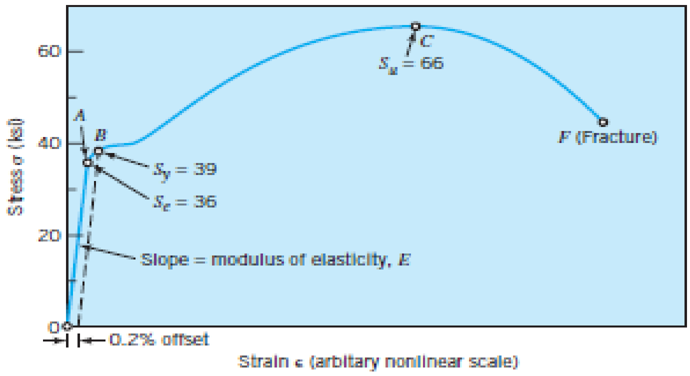


Figure 9. Stress-strain curve for hotrolled 1020 steel (Juvinall et al., 2011, p. 90).

Several different mechanical properties are visible in the presented stress-strain curve. Point A for example is the elastic limit (S_e). It is defined as the point of highest stress that the material resists while still returning to the original position while unloaded. After this point, material shows partially plastic response to added loads. This point also is an approximation of proportional limit at which the stress strain curve deviates slightly from a straight line. Conventional Hooke's law applies below this point. The slope of the curve (between origin and proportional limit) is referred to as the modulus of elasticity or Young's modulus (E).

The yield strength (S_y) is shown in the figure 9, as point B. It is at this level of stress that significant plastic yielding starts occurring. While for ductile materials, onset of this point can occur at a definable level of stress, for other materials it can be a gradual process. When it is so, yield strength is determined by offset method and in the figure 9, this is represented in point B which signifies a yield point of the material at 0.2 % offset. (Juvinall et al., 2011, pp. 90-91.)

For appropriate material selection, the most appropriate method is to identify the desired attribute profile for the design requirements and then finding the best match with available and real engineering materials. The process called "translation" is required at this stage to analyze the requirements of a design in order to identify the constraints that it can impose on material choice. When materials which cannot meet this constraints are removed, it helps to narrow down the choices. The selection can be narrowed further by identifying those materials that can actually maximize the performance of the design while also meeting the constraints. Figure 10 for example highlights important material selection criteria such as the function, the objective, constraints and other free variables. (Ashby, 2005, p. 81.)

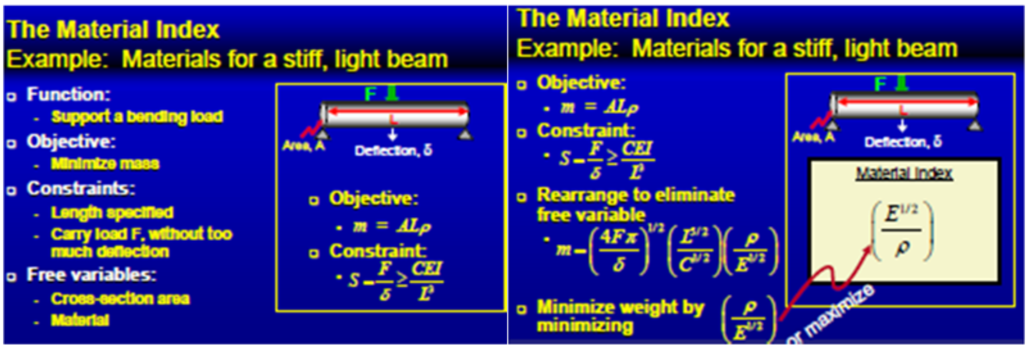


Figure 10. Example for section of material condition (Gregory, 2005, pp. 24-25).

2.7.1 Material for chassis

In modern robotic and automotive design, the material used should be light and the lower body part of the vehicle should also weigh less. Most of the robotic platform are manufactured by using light weight material. The choice of material is also important because different materials have different physical and mechanical properties. Most of the manufacturing processes such as joining, machining, heat treating are dependent upon the physical and mechanical properties of the material chosen.

In the early stages of robot and automobiles development, wooden structural parts were used. However, with the improvement on robotic and automobile technology the movement is at higher speed with higher motor vibrations which can cause problems with reliability and durability if wooden structural parts are used still. For these reasons, chassis frames are made by steel. Increasingly, aluminum and composite material are used because of their strength and light weight. In this section, various mechanical and physical properties of different materials are discussed.

Steels are widely used in construction and automobiles sector due to their high tensile strength and low-cost. Steel are alloys of iron mixed with other elements and mostly contain carbon. The density of steel is 7850Kg/m^3. Due to recent improvements in fabrication technique, steel quality is improving further still. It consists of wide range of mechanical and physical properties such as stiffness, strength and ductility; which are suitable for manufacturing chassis frame. (Happian-smith, 2001, p. 47.)

Most modern vehicles also use aluminum alloys to construct chassis frame. The advantage of aluminum and its alloys is that they weigh less and they have damping capacity and dimensional stability. The density of aluminum is 2700 Kg/m^3 which is three times less than that of steel. Specially, aluminum with 6000 series have high strength with weight ratio. However, the disadvantage of aluminum and its alloys is that they have a low fatigue limit.

Similarly, the advantage of using titanium and its alloy is that they are resistant to corrosion, are non-magnetic, have low thermal conductivity and have a very good strength to weight ratio. Therefore, it is perhaps the best material to prepare chassis but it is very expensive and difficult to machine. (Juvinall et al., 2011, p. 96.)

Additionally, composite materials can also be used in preparing chassis. Usually, these materials are used to make interior of the vehicle rather than the chassis frame. Although polymer composites and metal matrix composite material might have applicability in the future, they are still being researched and not commercialized extensively yet.

2.8 Finite element method

Finite Element Analysis (FEA) is a numerical method for solving engineering problems. When the problem consists of complicated geometries and loadings without the possibilities of deriving analytical solution, this method is recommended. Finite element analysis is conducted by generally following three important steps: preprocessing, analysis and post-processing, each of which are discussed in this section.

Preprocessing: This step involves constructing a model of the component that is to be analyzed. This is done by first dividing the geometric shape into different discrete elements which are connected with various nodes. Some nodes in this model can have fixed displacements whereas others can have prescribed loads. In this thesis, graphical "preprocessor" software was used to superimpose a mesh on preexisting computer aided design file and finite element analysis was conducted with computerized drafting and design process. This step was followed as otherwise it would be rather tedious process.

Analysis: In this step of the process, the dataset prepared by the preprocessor is fed into the finite element code itself. These are then solved as systems of linear and nonlinear algebraic equations. Commercially available programs can have codes with large libraries of elements which can be appropriate to many different types of problems. Some examples are shown in figure (see the figure 11).

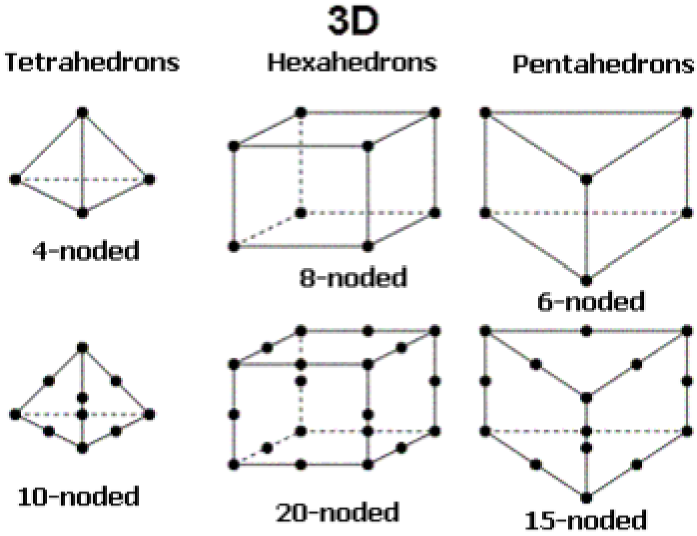


Figure 11. Some example of 3D finite element elements (Martins & Kövesdy, 2012).

Post-processing: In this step of the analysis, graphical displays are generated to visualize the results related to trends, displacement, stresses and other hot spots. A postprocessor software can display varying levels of stress in the model in colored contours akin to pothoelastic or moire experimental results. Thus, numerical solutions to even very difficult stress problems can be generated easily by using FEA.

Despite the use and popularity of these commercially available software, the major disadvantage is that the codes are invisible and incomprehensible to the user and makes it difficult for the user to understand the underlying mechanisms in generating results (Roylance, 2001, pp. 1-2.) The other disadvantage is that although the stress results are shown, FEA analysis might not necessarily explain the relationship of stress with other important factors such as other material and geometrical properties of the component. It is also possible that results derived can easily be incorrect due to error in inputting data into the system. Therefore application of FEA should be done with care by the designer and should supplement this analysis with other possible closed form and experimental analysis.

3 DESIGN

The word “design” itself is derived from the Latin word “dēsignāre”, the meaning of which is to designate or mark out. Obviously, this is vague and denotes wide ranges of meaning. According to Norton (2006, p. 3), design can be defined as “the process of applying the various techniques and scientific principle for the purpose of defining a device, a process or a system in sufficient detail to permit its realization”. Or in other words, the objective of any design process is to choose appropriate material, parts of right size and shape and appropriate manufacturing process leading up to a resulting design or component part that is expected to perform its intended function without failure.

When the design does not consist of moving parts, the design process is much simpler as it only amounts to structural design. Even if the structural parts consists of moving components, if the motion is slow and acceleration negligible, static force analysis is enough. However, if the designed component has significant acceleration, the accelerating parts become “victims of their own mass” and in such situation, dynamic force analysis is required. (Norton, 2006, p. 4.)

3.1 Design process

Design process involves multiple steps and each phase of the design process have different functions, costs and reliability. Each phases of the design process have distinct rules and instructions which leads to the next phase. Different stages of a design project are illustrated in the flow chart in figure 12. More broadly, design process is divided into three major phases: concept, development and execution phase which are explained further in following subsections.

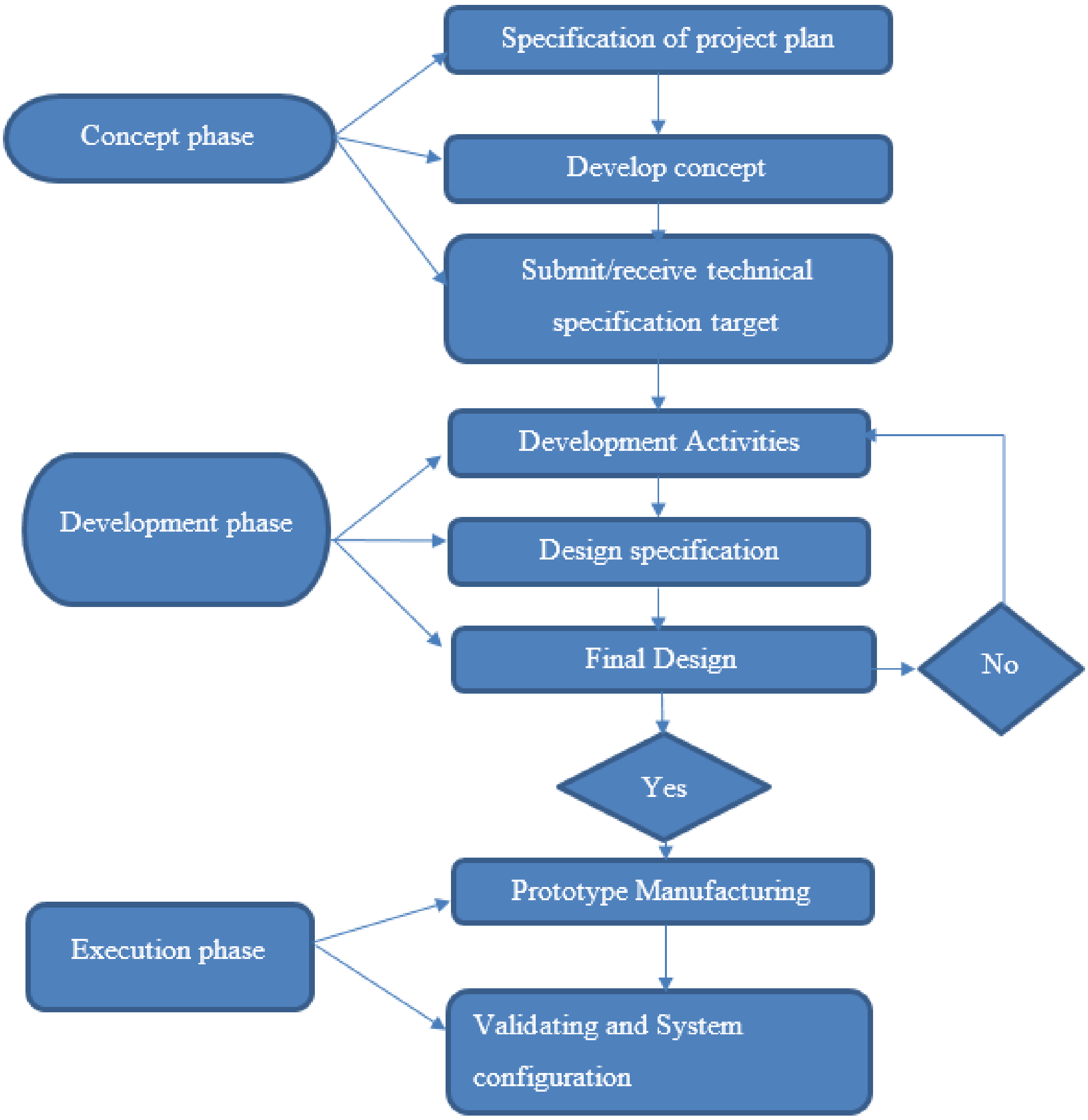


Figure 12. Flow chart for designing process adopted from (Heissing et al., 2011, pp. 450-465).

3.2 Concept phase

The idea behind the concept phase is not to find revolutionary solutions to problems but to validate previously defined concepts or to make the final selection between alternative solutions. Due to this, the freedom of the developer at this stage is already quite limited as the development engineer is involved in selecting between already identified and mature technology solutions. (Heissing et al., 2011, p. 456.) Generally, this concept phase is also divided into three major sub-phases: specification of the project plan, concept development and execution phase.

3.2.1 Specification of the project plan

Since the goal of this project is to design a mobile robot chassis frame, it is important to define specifications and requirements. The specifications and requirements of this project came from the mobile robot application for general indoor assembly purpose. The document provided by the project manager was used as the reference point during concept development and to effectively define the phases of the project.

Most of the robot consists of complex motor, controller, manipulator and other components. All of these different systems, module and individual component are simultaneously mounted or fixed on a chassis. As this project involved developing a tele operated mobile robot, the parameters and component specifications are summarized in table 1.

Table 1. Part and other parameter specifications defined in the project plan.

Chassis Constrain	**System parts**	**Parameters**
Two UR 10 robotic arm to be connected similar to human shoulder	UR10 robotic arm	The weight of each UR10 arm weighing 30 kg
		Shoulder height should not be less than 800mm
		They should be placed in front of the robot.
		Each robot arm has pay load of 10 kg.
Provide two robot arm with controller in the mounted space	UR 10 controller	10Kg weight of each arm controller mounted with chassis frame.
Mounted with chassis frame	Battery	16 piece of battery.
		Each battery weighing 2.3kg
		They should compact as a 1 piece.

Table 2 continues. Part and other parameter specifications defined in the project plan.

Chassis Constrain	System parts	Parameters
Provide landing space at the top of the chassis frame	Quadcopter	4kg
		Dimension 438*451*301mm
Electronic parts	Advantech, DC/DC converter, arm controller etc.	Provide the space in such a way that they can access any situation
		Space for wiring and extra component that can be required in the future
Frame should be connected with the bearing point provided by modular system designer	Electronic part ,Drive modular system	Chassis frame should be mounted on bearing mounting position.
		Modular system should be inside the chassis frame.
Manufactured by conventional method	Chassis frame	Should not be more than 80kg.
		Length and width should be within 1600*800mm.
		Manufacturing process may be laser cutting, CNC milling, welding or other available process
		Low cost
Mass of overall robot		Should not exceed more than 300Kg

3.2.2 Concept development

The idea behind this stage of the design process is to generate ideas that is capable of meeting the project specifications and goals. At this stage, it is important to review past literature that deals with development of a proper robot chassis frame. The main goal of this phase is to implement the information gathered to turn into a concept of chassis frame design. It is also important at this stage to gather ideas and inspiration and to visualize the concept with specification.

The components of a robot

Before designing a robot, it is necessary to have background information about dependable parts of the robot. In this section, different components of the robot are described as per the specifications outlined at the beginning of the project.

Omni wheel: One of the typical application of Omni wheel (Swedish wheel) is that it is compatible with mobile manipulation. While designing a robot, the use of Omni wheel can reduce the degree of freedom of the manipulator arm and due to mobile robot chassis motion, robotic arm mass can be saved in gross motion (Siegwart & Nourbakhsh, 2004, pp. 41-45.) Omni wheel and manipulation are positioned well when the manipulator tip does not affect the movement of the base Omni directionally. 3D model of an Omni wheel is presented in figure 13.

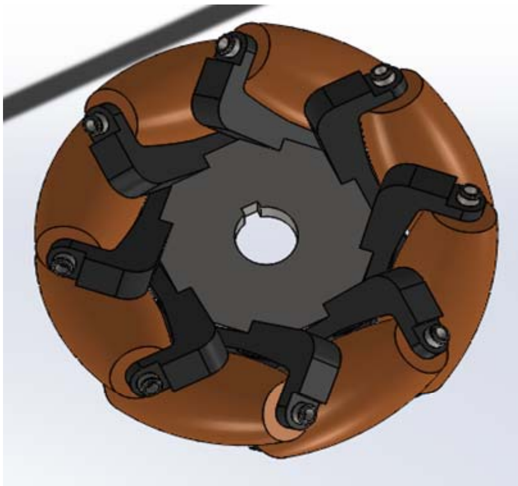


Figure 13. 3D-model of an Omni wheel.

UR10 Robot: In this project, UR10 Robot was used as a tele operated mobile robot arm, although it itself is a robot. UR10 robot has the capability to perform different operations such as packaging, assembly, picking and placing. It is more capable of picking and placing work due to its length of 1300 mm. In this project, a tele operated mobile robot is developed consisting of two UR10 robot which will serve as robotic arms for the mobile robot. Figure 14 (a) illustrates UR10.

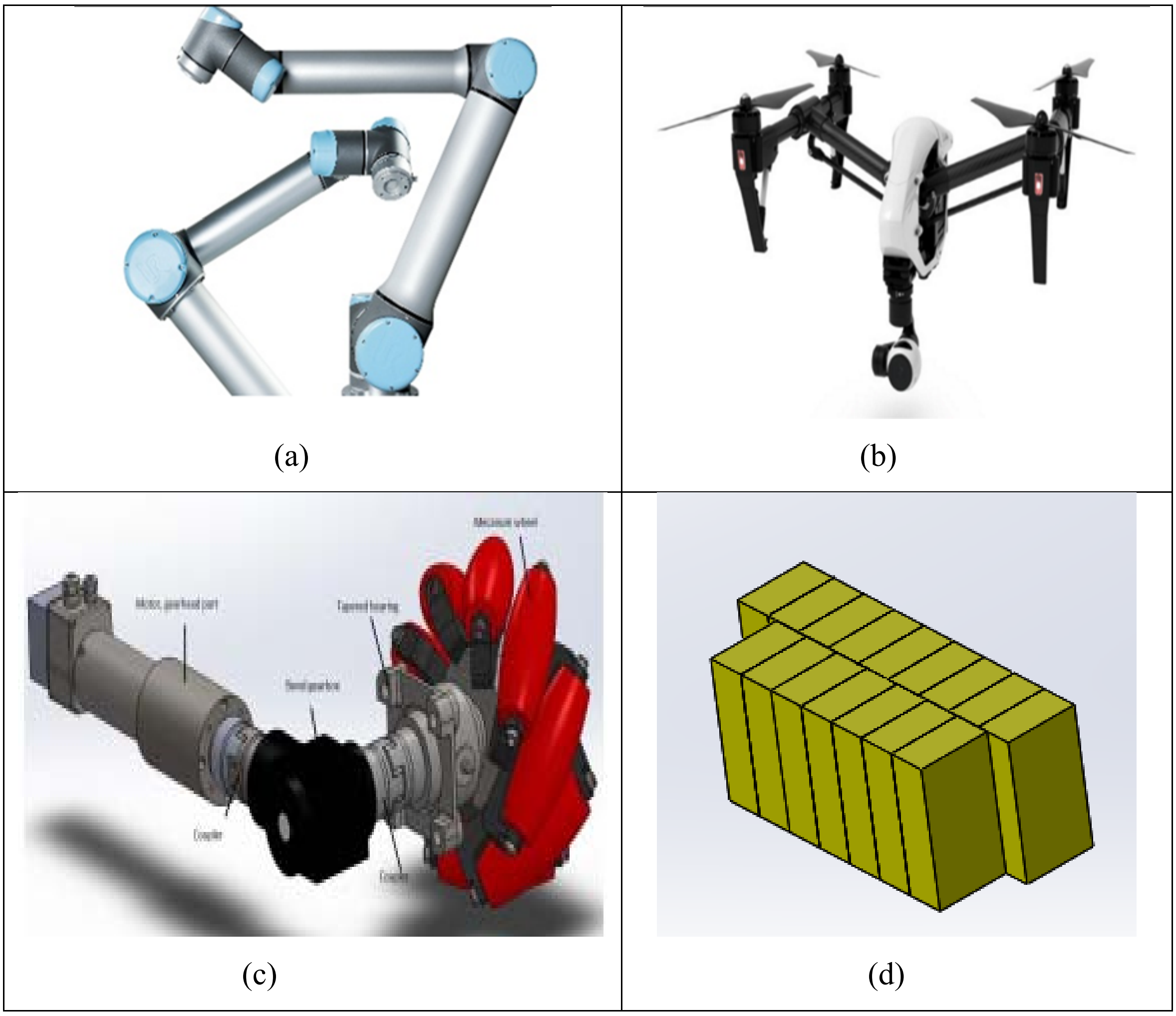


Figure 14 . (a) UR10 robotic arms (Bélanger-Barrette, 2015), (b) DJI inspire 1 drone (Calvo, 2015) (c) modular system with Omni wheel (d) 16 piece of battery.

Drive modular system: The drive modular system is composed of coupler, bevel gear, shaft and maxon motor with a sensor and brake. They are often combined with Omni wheel and Timken bearing. Each wheel of the drive modular system move independently and therefore they contain four drive modular made up of similar parts. This project also consisted of other members in the group, one of which was involved in designing the drive modular system alone. Drive modular system is illustrated in figure 14 (c).

Battery: For the robot to operate, high powered lithium cell manufactured by GWL power battery were used. Each battery has a nominal voltage of 3.2 V. To derive 48V of power to operate the robotic arm, for example, 16 battery cells were used which weigh in total 360.64 N. The advantage of this battery is that it is small in size and is lighter than other forms of batteries. Additionally, they are suggested to be appropriate for traction application. (GWL power Ltd , 2015.) An illustration of compact 16 cell in a 3D-model is provided in figure 14 (d).

Visualization with specification: The idea behind visualization with specification is to create ideas behind how different components should look like, where it should be mounted and which component should be prioritized by function and mounting place so that the chassis frame design is the most effective. Figure 14, for example, illustrates the most important component that are decided to be part of the robot. Other important items such as controllers are, however, not illustrated in the figure. The weight and dimensions of different components are summarized in table 2.

Table 3. Weight from drive modular system.

Part name	**Mass per part* number of parts**	**Total mass(kg)**	**Weight (N)**
Gearhead	3*4	12	117.6
Motor	2.4*4	9.6	94.08
Controller	0.33*4	1.32	12.936
Brake	0.18*4	0.72	7.056
Coupler	0.92*2	1.82	17.836
	1..08*2	2.16	21.168
Gear box	4.5*4	18	176.4
TimkenTapered bearing	3.2*4	12.8	125.44
Mechanum wheel	7.2*	28.8	282.24
Others		3.2	31.36
Total		90.42	886.116

After the visualization process of different components of the robot, the physical specification of different components of the robot are provided in table 2 and 3, which will aid in further development of the chassis frame.

Table 4. Weight and dimension of robot arm, controller and DC/DC converter.

Name	**mass* number of parts**	**Total mass(Kg)**	**Dimension in mm**
UR 10 robotic arm	30*2	60	1300 length and base diameter 170
UR 10 arm controller	10*2	20	426*196*194
Advantech computer	4*1	4	220*210*196
Battery	2.3*16	36.8	203*114*61
DC/DC converter(48V)	1.94 *4	7.76	295*127*41
DC/DC converter (12V)	0.48*3	1.44	159*98*38
Inspire 1	2.935*1	2.935	438*451*301
Total		135.935	

Idea and inspiration: In order to develop a viable concept, it is necessary to get inspiration from previous designs, information and already developed technology. Before developing a concrete concept, ideas can be generated by comparing the functionality with other design, location of the component and relocation of their system. Some inspirational robot which resemble the functionality, component placement and expected technology are presented in figure 15.

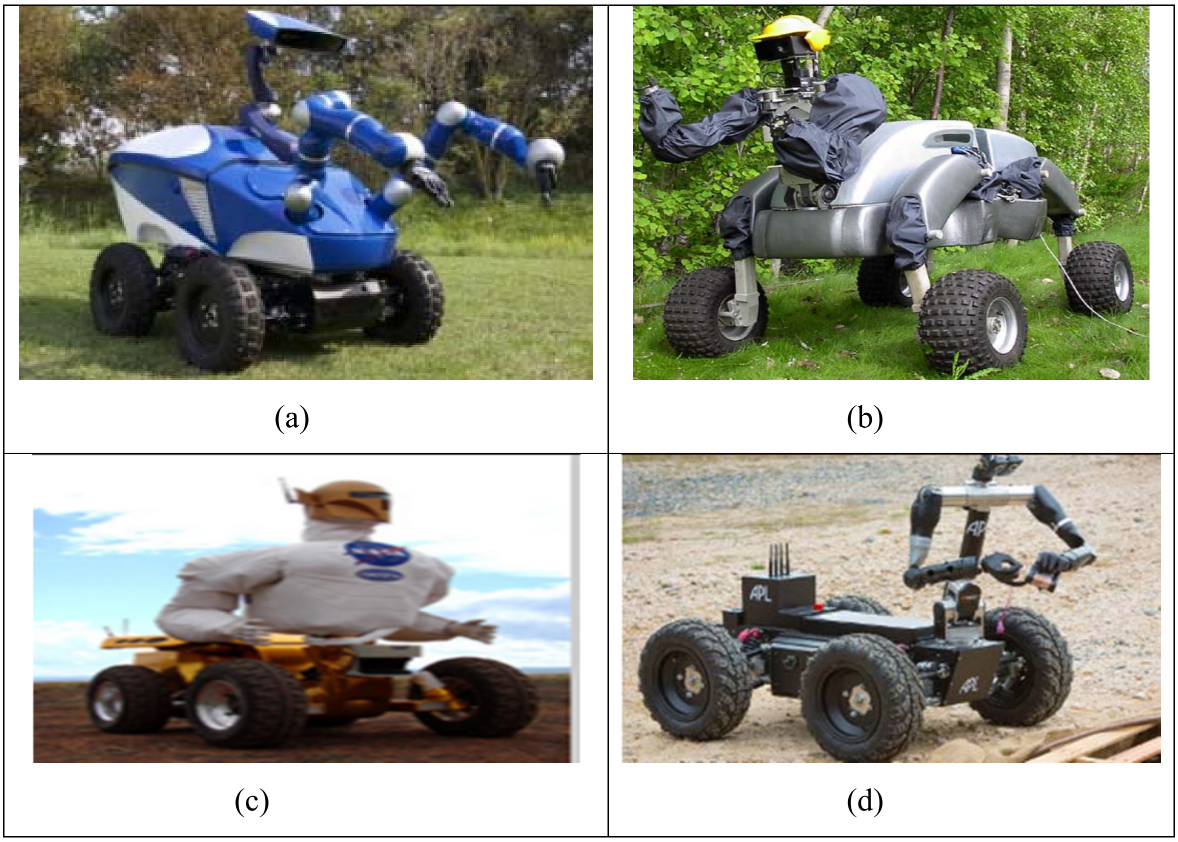


Figure 15. (a) Centaur rover (Jullian, 2015), (b) Work partner robot (Aalto-University, 2009), (c) RobonoutR1Bon centaur (Bibby, 2013) and (d) AMBOT´s EOD (Ambot, 2015).

These images presented above resemble somehow the idea of the project even though they use more advanced technology and are built with higher cost. It is also inspiring to sketch and find the correlation among different components. It facilitates brainstorming process in collecting data, note making, sketching and visualization of the concept. Therefore, it together leads to ideation and invention, suggesting creative alternative design approaches. (Norton, 2006, p. 6.)

For the design of the chassis frame, 3D-CAD (Computer Aided Design) is Computer base tool for assist the creation and analysis of a design. Software such as Solid-Works was used as sketching and concept visualization tool. This software also speeds up the creation and delivery of designs as 3D-CAD models can help to communicate complex technical details visually. Since, Solid Works consists of built in intelligence, it avoids the guess work during 3D design process. It also minimizes the training period as it allows quick, detailed and error free designs. Solid Works also has automatic manufacturing dimension features in 3D, checks the dimensional completeness and graphically displays dimensional status on 2D drawings. Since Solid Works also has inbuilt automatic interference and collision detection capability, it ensures that all components fit together in the physical prototype, thus reducing cost and shortening the product development cycle and increasing the time to market. (Solid works, 2015.)

Submit /receive specific technical target: During the first phases of the meeting, a conceptual space frame was made, on the basis of a simple suspension system as shown in figure 16. In figure 1a circle with black and white spot show the center of mass while the space frame was made using the dimensions of the suspension system. In the image, the position of the robot arms and the battery are also shown in their respective position. It is obvious from the figure 16 that while using this suspension system, center of mass cannot be achieved in a desired position. When this fact was presented in the project meeting, the project manager cancelled the idea of using the suspension system. Another issue emphasized during the project meeting was that the robot arm should be positioned as if hands were positioned in a human shoulder or supported horizontally. Besides these, it was also suggested that the use of Omni wheel in the outside environment is not desirable due to the difficulty in studying and controlling its motion. Usually, the targeted function of the robot is to move in indoor environment where the surface is smooth and plain. That is why it was suggested to build a robot which does not consist suspension system.

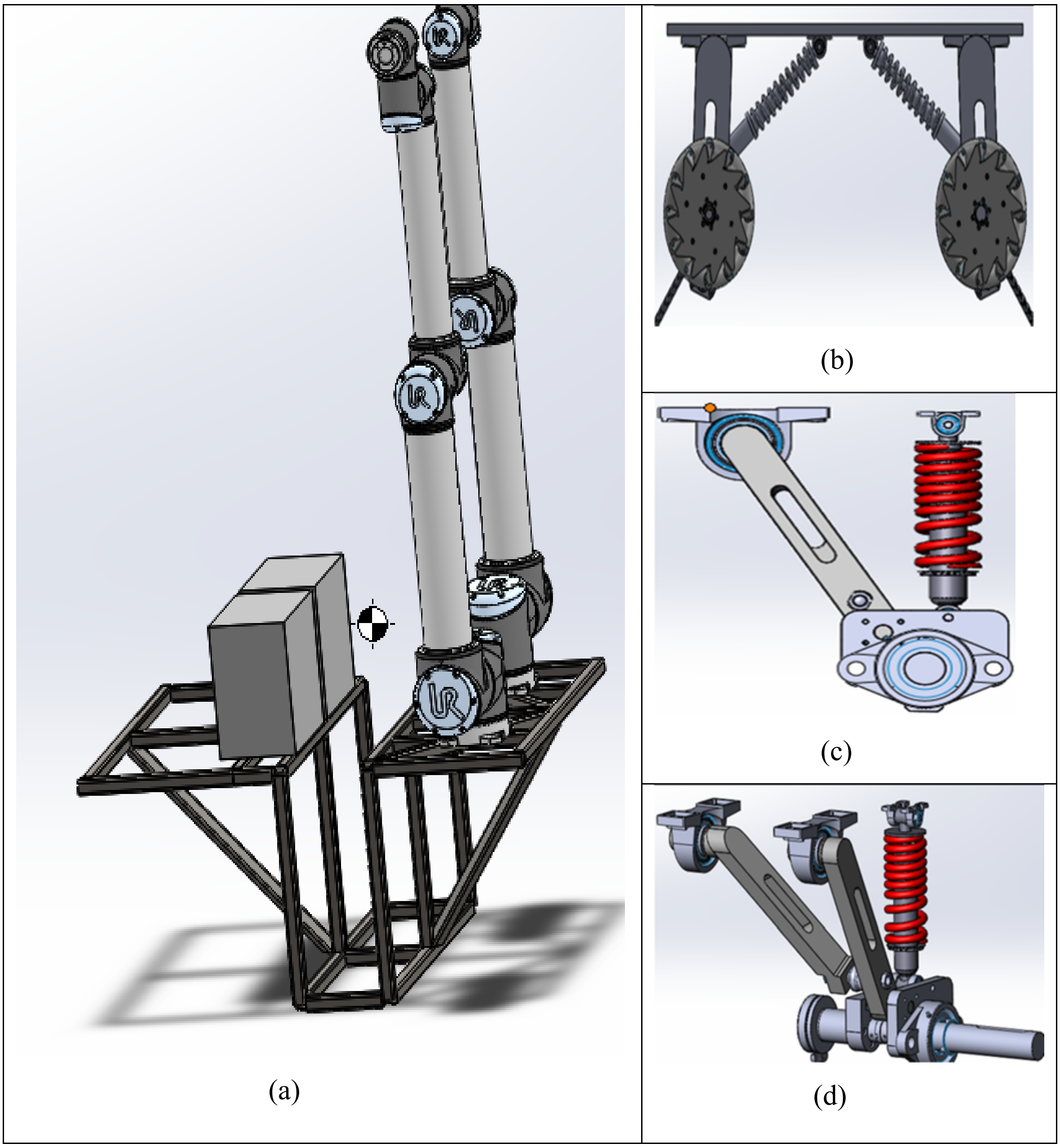


Figure 16. (a) Spaceframe with robot and battery; (b), (c) and (d) suspension system in different view.

3.3 Development phase

After the change in specifications, the end goal was much clearer as the suspension system were to be removed and the robotic arms had to resemble the human shoulder structure. Besides these new specifications, other characteristics of the chassis such as symmetry, center of mass and parts mass distribution of the overall body were additionally considered.

One additional and important design consideration is the counterbalance weight. The weight of the robot arm consists of around 25% of the total weight of the robot as the specified weight of the robot should not be more than 300 kg. Similarly, the weight of the battery is also around 12% of the weight of the robot.

The fulcrum rule states that in a bar balance, the clockwise torque equals to the counterclockwise torque (Briggs, Gustafson, & Tillman, 1992, p. 213).Free body diagram for fulcrum rule shown in figure 17(a). By applying this definition, solution can be derived by calculating as follows:

$$80 * x = (1600 - x) * 36.8 \qquad (1)$$

Where x is the distance. From equation 1 the value of x can be determined as 504.11 mm. From this calculation, it is possible to determine that center of mass lies around 1/3 from the front rated weight which will lead to good counter balance weight. This is the initial assumption.

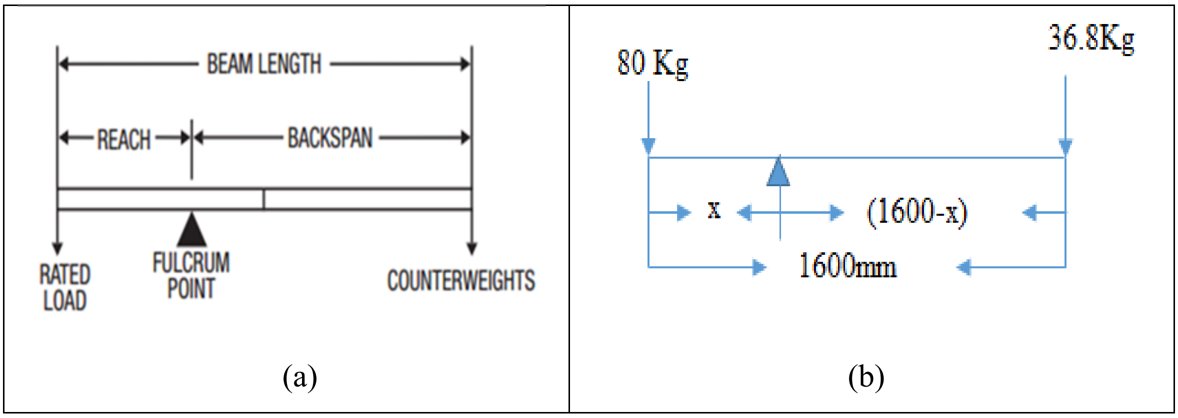


Figure 17. (a) Fulcrum rule in general (Spider, 2013) (b) Free body diagram for counter balancing.

Since robot arms are heavy and are mounted on top of the robot chassis it is possible that the point of the center of the mass is above the desired level. This could possibly be canceled by chassis mass as it can act as a counter weight and a balancing factor to lower the center of mass. Due to this reason, it is desirable to use material which has high mass density, cheap and is strong. Since all of these conditions are satisfied by steel, it will be used as a material to design the chassis frame.

3.3.1 Development Activities (a)

After previous phases, using steel as material, square tabular beam and angle beam were used to make the ladder type chassis frame. These components were easier to model and are also easily available in the market. The detailed development activities are elaborated in this section.

Define dimension for wheel drive modular: The drive modular consists of four wheels that drive independently. The dimensions were defined on the basis of result from fulcrum analysis and given specifications. As specified, the chassis frame should be positioned inside 1600*800mm. The dimension length 1600 mm includes both the distance of the wheel base and the additional length left to provide freedom to add additional components that might be required later. Track width (TW) is defined as the distance between center points of Omni wheels when it is between front to front or rear to rear wheels. In contrast, wheel base (WB) length is defined as the distance between the center of front and rear wheels (Heissing & Erosy, 2011, pp. 18-19.). The system are illustrated in figure 18. Since the width of one Omni wheel is 130 mm, taking into consideration that the overall dimension width is 800 mm, track width is now 670mm. The distance of the wheel base is 1060 mm and the wheel track is fixed at 670 mm.

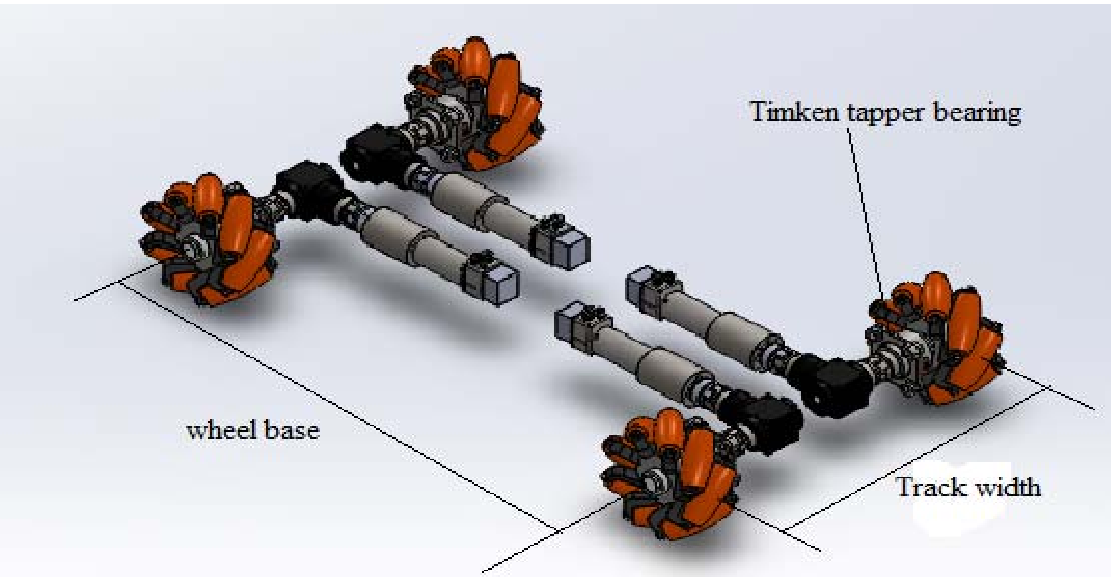


Figure 18. 3D- modeling of Drive modular system with Omni wheel present with wheel base and track width.

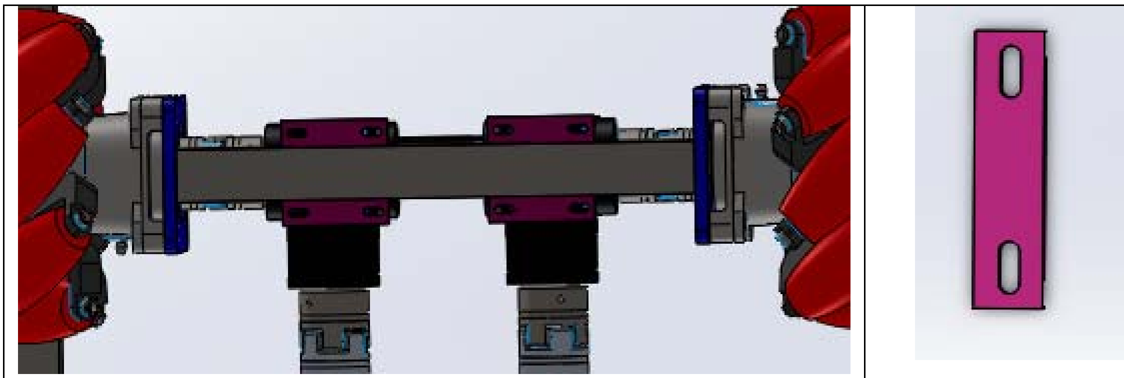
After fixing these dimensions, the basic construction will now be easier. To start the construction process, it is necessary to determine the position of the parts that should be mounted on the frame and the length of the beam. The starting point for frame design is the position of the Timken tapper bearing hole where the frame structure will be mounted.

Chassis mounting with Timken bearing mount point: Since the Timken bearing already contains four holes which are mounted by M12 bolts, another connecting part with four holes positioned accordingly, preferably as a plate as shown in figure 19(a) is required. The middle of the connector part is a semi-circle that allows a square tube to be connected at the bottom wider part. This part is made of steel and the thickness of the plate is 10mm. The one used in this project was produced by a company Ruukki's and the name of product is Optim 900 QC. It was chosen because it is ultra-high strength structural steel with good workshop properties.

(a) (b) (c)

Figure 19. (a) 3D- model of a bearing connecter (b) 3d-model of a Timken bearing (c) Assembly of bearing connector with Timken bearing.

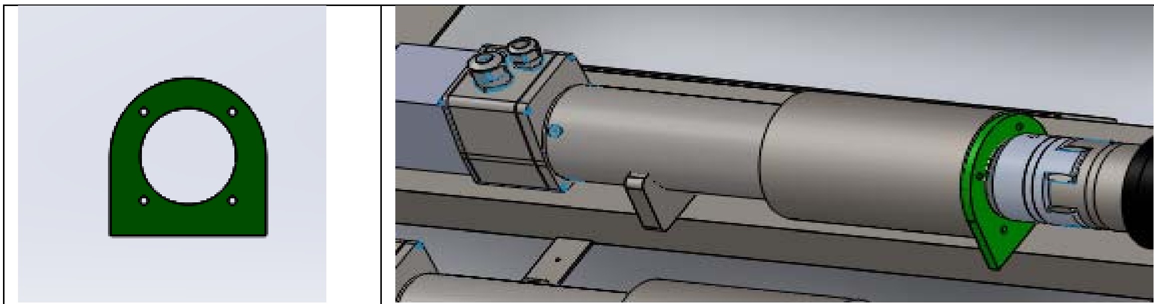
Bevel gear support: To support the bevel gear a square plate with two slots was made. The component was made from a steel plate with the thickness of 5 mm as shown in figure 20 (b). Two slots were made with tolerance level to match the assembly requirements. The parts welded into the square beam are illustrated in figure 20 (a). The constructed parts were welded on each side of the beam to support the bevel gear which was then connected by M4 bolt screws. The bevel gear is shown in black in the figure.



(a) (b)

Figure 20. (a)Assembly with bevel gear with its mounting part (b) 3D-CAD model of a bevel mounting part.

Motor mount: The motor mount is one of the most important part in the chassis frame. It exhibits high torque .The motor mounting part is shown in figure 21 (a) and it consists of four M6 holes in the outer part, and a big middle hole where the shaft and coupler passes through. The assembly of the motor and the motor mounting is illustrated in figure 21 (b).



(a) (b)

Figure 21. (a) Motor mounting part (b) Assembly of a motor and its mounting part.

Battery box: The width of the chassis frame is limited to 800 mm. Included at the back of the chassis, within this width, was also battery with 16 pieces; 7 pieces at the first row and 9 pieces in the second row. The motive behind placing the battery box at this position was also to act as counter balance to the robot arm. Battery boxes were made with the angle beam of 2 mm thickness. They were welded together into a rectangular box as shown in figure 22.

Figure 22. Battery place in chassis frame.

Ladder chassis frame: Ladder chassis frame was constructed after mounting the drive modular system and placing the battery box in their respective places. Square beam was used to construct this section. 3D-CAD image of the frame is illustrated in figure 23.

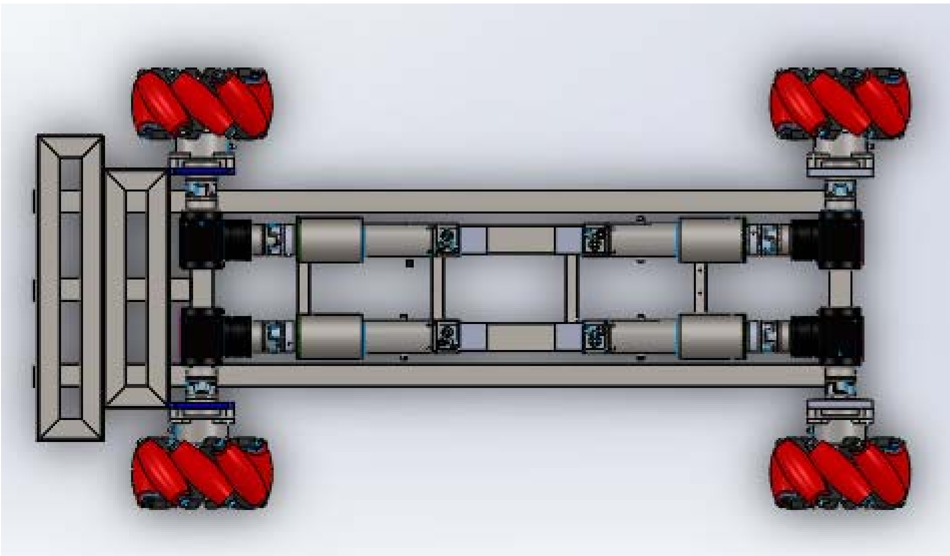


Figure 23. Ladder chassis frame for robot.

Shoulder like T-joint: Tubular pipe were used to construct the T joint. The thickness of the pipe is 4 mm with the diameter of 101.6mm. In order to mount UR10 robot arm in the structure, circular plate of 6mm thickness was constructed and holes were made in appropriate places. Shoulder like T-joint is illustrated in figure 24.

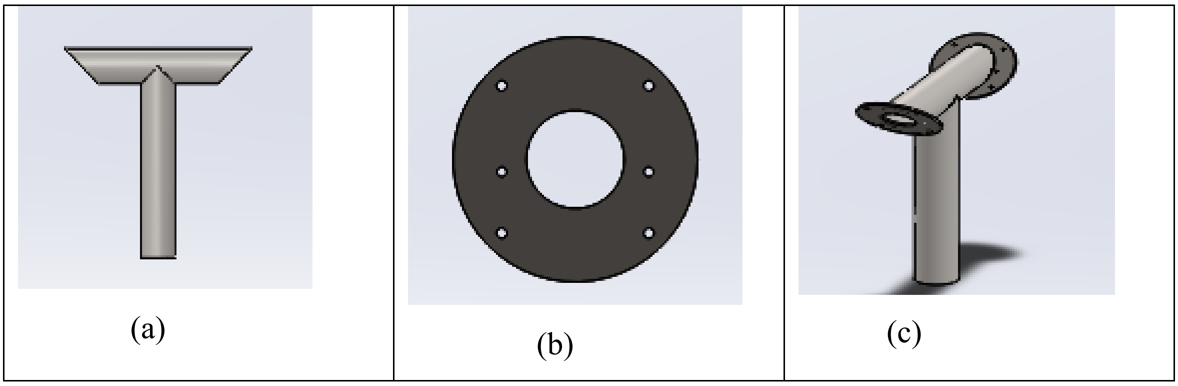


Figure 24. 3D-CAD model of (a) tubular joint (b) UR 10 robot mounting point (c) Assembly of T-joint with UR 10mounting part.

Construction for electronic component and resting place for T-joint and quadcopter landing support beam: Since, other components also need to be mounted in the ladder chassis frame, it is necessary to use square beam and plate structure. The final basic design of the chassis is illustrated in figure 25. Most of the beams and plates are connected by welded joint.

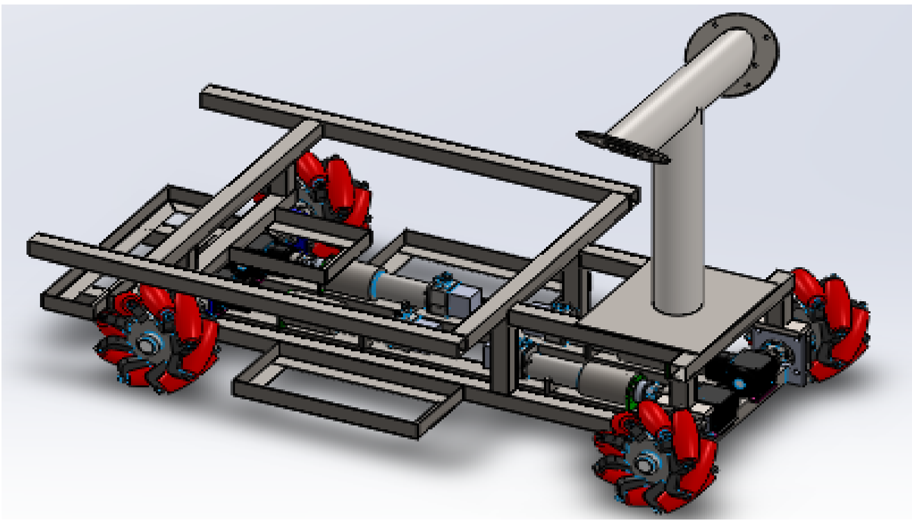


Figure 25. Full construction of chassis frame.

3.3.2 Design specification (a)

After the inclusion of all electronic component in the assembly, analysis was conducted to determine the center of mass. This analysis is illustrated in figure 26. The result obtained from this analysis are further summarized in table 4 which directly follows figure 26.

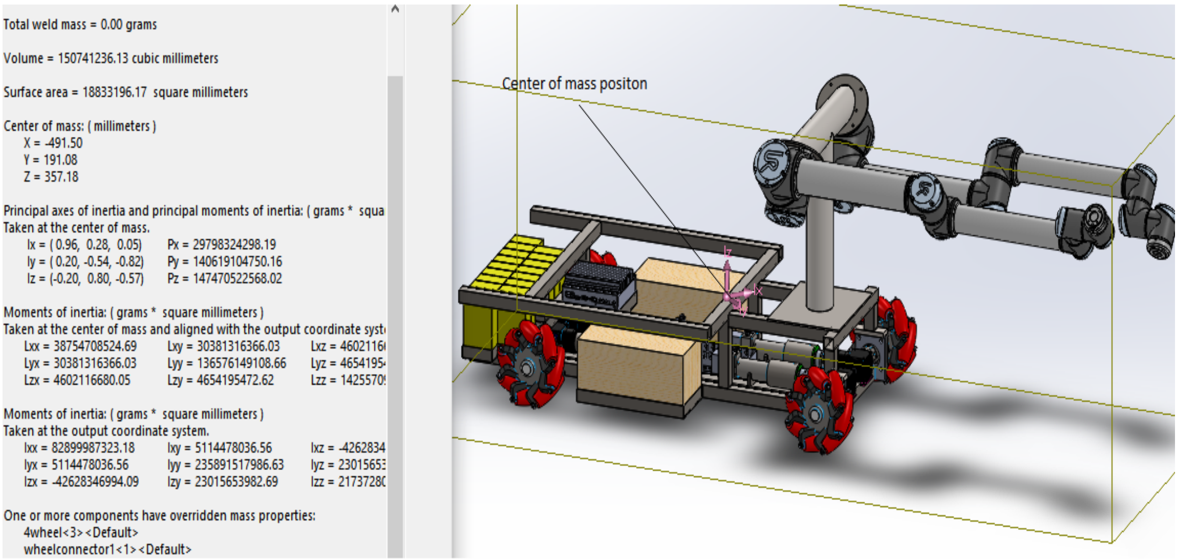


Figure 26.Complet robot assembly with their respective component.

Table 5. General results of the chassis frame for design.

Specification	**Result and process**
Position of center of mass	491mm back from front wheel center, 440 mm toward center from front left wheel, 329mm from ground level.
Total chassis frame mass	Around 65Kg from Solid-works mass calculation.
Overall robot dimension	1593.5 length and 800 mm width
Manufacturing and joining process	welding, machining and cutting

In summary, the designed chassis frame fulfills the basic project specifications after considering symmetry, mass distribution, center of mass and inertia. The center of the mass achieved was acceptable considering the situation even when the UR10 robot arm is fully extended, as this is critical to consider the robot in motion.

3.3.3 Presentation of the design

The above presented design of the chassis frame was presented during a project meeting and the project manager and other experts commented on the initial design. More ideas for improvement were suggested as below:

1. There were too many individual parts so suggestion was made to reduce the number of parts.
2. Since all structure are welded, suggestions were made to reduce the welded joint as much as possible to achieve targeted tolerance.
3. Suggestions were made to place the electronic component in easily accessible positions to facilitate easy maintenance if failure occurs.
4. Suggestions were made to make the design of the base frame friendlier to facilitate easy assembly and disassembly.
5. Since the components were placed in a compact manner, suggestions were made to increase the space in the chassis frame so that there is space remaining for additional electronic components in the future.

From these comments, it was apparent that the presented chassis frame do not meet the specifications of the desired final design. Therefore, following the design process as presented in figure 12, it was necessary to revise the development phase once again. However, many of the design elements such as the T-joint, the battery box as well the concept of the mass distribution in the chassis frame were accepted and not necessary to revise.

3.3.4 Development activities (b)

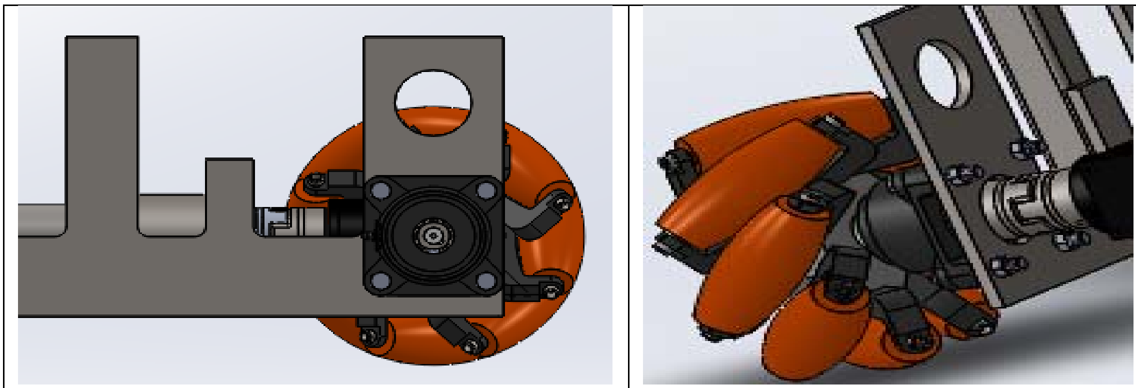
After reviewing the dimensions of the modular system and after additional speculation, it was decided to replace the square beam with a plate with complicated dimensions and also having higher strength. This reduces the number of components and also the number of welded parts. This beam should be designed in such a way that it directly connects to the Timken bearing and supports the weight of the robot acting like a horizontal beam.

Frame mounting with Timken bearing point: Based on the dimensions of the plate connector in the previous design, new plate beam was made with the total length of 1527 mm. A vertical structure was also added to act as a beam. Quite simply, the horizontal square beam was replaced with a single plate. The overall dimensions of this design is presented in (appendix I) and the 3D-CAD model of this new structure is shown in figure 27. The new design consists of holes and chamfer which will at the same time make the mounting process easy as well as replace lots of components. The material chosen for this structure was

Ruukki's Optim 900 QC, with tensile strength of 900-1200 MPa and yield strength of 900 MPa.

Figure 27. Single plate design as a beam.

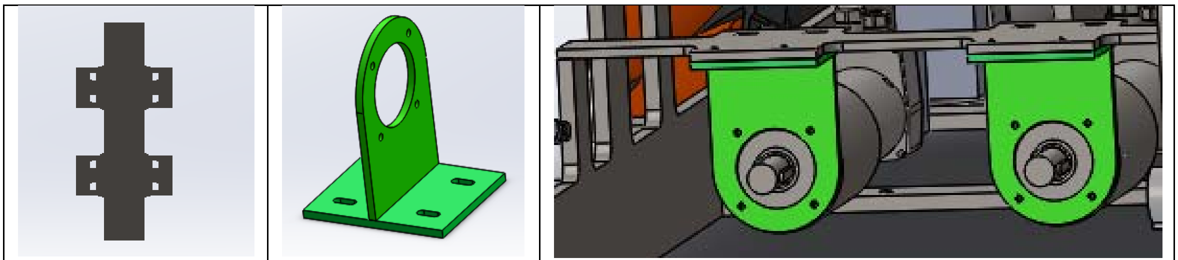
The beam mounting with Timken bearing is illustrated in figure 28. It is mounted by using four M12 bolts that are rigid enough to carry all loads and forces. By mounting it this way, there is more space left in the middle to allow more electronic components. Single beam plate with the same dimensions was constructed on the reverse side for symmetry considerations.



(a) (b)

Figure 28. Single plate beam mounting on Timken bearing.

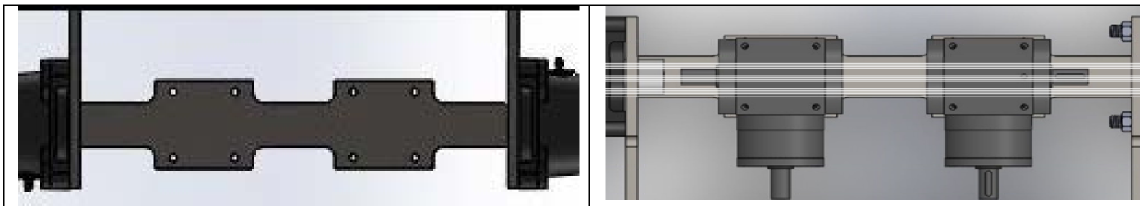
Motor mounting: For constructing motor mounting, three different parts were designed. One of the parts act as a beam (i.e.; motor mounting beam) where it is welded with main plate beam. Motor mounting beam contains slots that provides space in mounting motor to the structure. This part is illustrated in figure 29 (a). The thickness of the plate is 10mm. The second part is a structure that helps to connect other components to the base of the motor. This T-like structure is shown in figure 29 (b). The first structure that consists of slots is welded to the beam. The T like shape is attached with M6 bolts in the welded structure and it consists of a circular hole in the center where the motor is mounted. This design is illustrated in figure 29 (c). Since all of these parts are connected with screws and nut bolts it provides the freedom of assembly and disassembly which facilitates the repair and modification process. In summary, at this phase, motor mounting beam and T-like shape to mount the motor to the beam were constructed.



(a) (b) (c)

Figure 29. Motor mounting parts and assembly.

Bevel gear box mounting: In order to construct a mounting structure for bevel gear box, a single plate with holes of 5 mm thickness was designed. The tolerance limit of clearance holes is explained in (appendix II). As the beam is welded, there is no guarantee of high tolerance due to the post-weld deformation. Single plate beam is illustrated in figure 30 (a). In this structure bevel gear is mounted with M6 screws in each cross slot holes as shown in figure 30 (b) which provides the top view. In this structure, couple of bevel gears were mounted, and other additional beams were constructed for other bevel gears at the reverse side to take into account the symmetry of the structure.



(a) (b)

Figure 30. (a) Bevel gear support beam (b) assembly of bevel gear and support beam with base beam

Ladder chassis frame: After mounting the drive modular system in the frame, 4 middle beam of same dimensions were constructed for single beam plate. This also helps to position two beams in parallel in a fixed place. Similarly, 10 extra extension beams were constructed for supporting controllers. The resulting fame looks like a ladder chassis frame as illustrated in figure 31. Battery box is placed at one end of the chassis frame. These plate beams now completely replace the previously used square tabular beams. This helps to reduce the number of total components and also makes the manufacturing process easier as they are similar to one another.

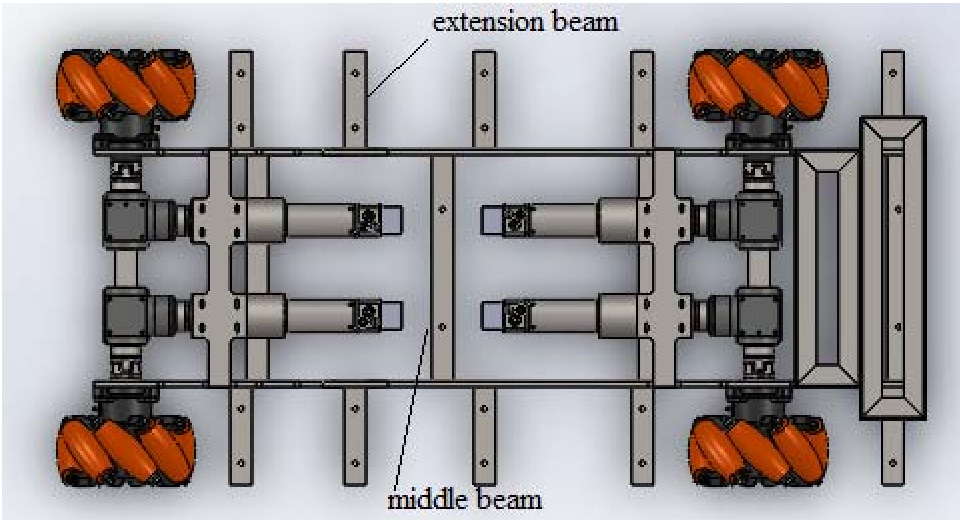


Figure 31. Ladder chassis frame with additional middle and extension beams with mounted modular systems

Space creating for electronic component by making second storey:

In order to create additional space to position electronic components, a second storey to the structure was constructed by using angle beams with the cross section of 40*40 and 3 mm thickness and mounting it to the beam plate. M8 bolts were used to mount this second storey. This design is illustrated in figure 32. The main idea behind constructing this additional layer was to provide space for electronic components such as Advantech computer and DC/DC converter.

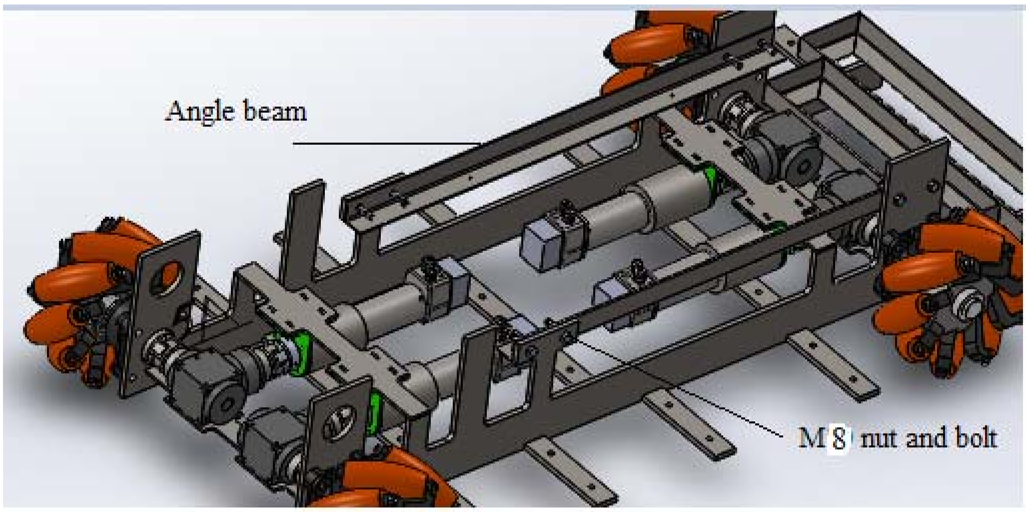


Figure 32. Angle beam mounting in ladder chassis frame.

Landing space for quadcopter and T-joint fixture: T-joint support base, which is X shaped structure, was constructed on the chassis frame by using Optim 900 QC steel of 10mm plate thickness. This material is capable of supporting the weight and movement of the robot arm as well as the weight of the T-joint structure.

The design specifications mentioned that the quadcopter should be positioned on the top of the robot body. To fulfill this specification, angle beam, square tube and mounting plate were connected to the frame by welding or using nut bolts. This also makes the assembly process flexible and easy. The constructed part of the landing support together with the T-joint are illustrated in figure 33.As provided in the specifications, quadcopter should land on top of the robot boy. To fulfill this requirement angle beam, square tube and mounting plate were constructed and connected either by welding or by using nut bolts. This also provides flexibility and ease in assembling and disassembling process. Constructed part for landing support and t- joint are shown in figure 33. Extra space was left behind in the construction (for example on top of the battery box) to provide space for additional electronic components such as the fuse.

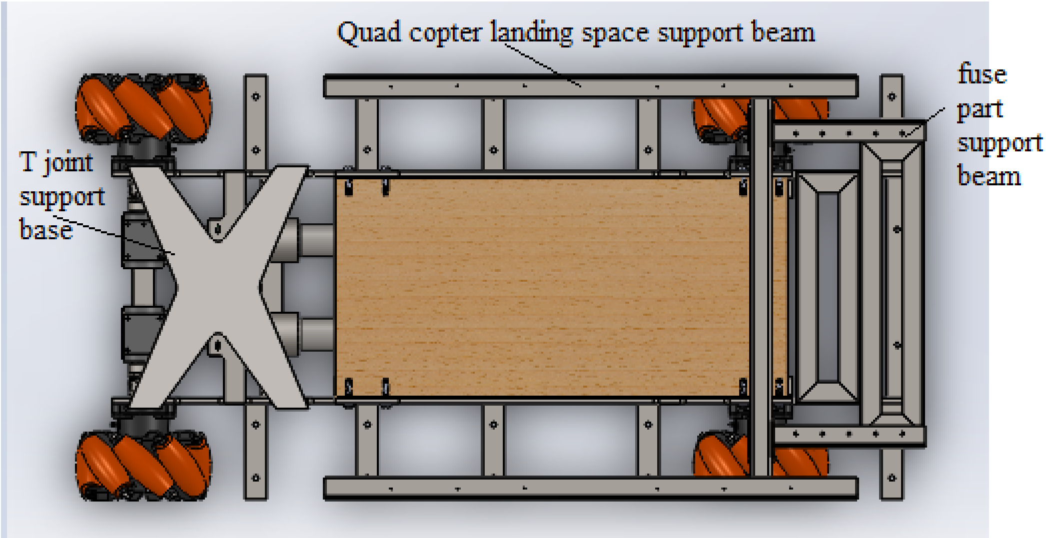


Figure 33. Chassis frame extended with landing space for quadcopter and T-joint.

3.3.5 Design specification and final design

In this way, by adding additional components and reviewing the given project specifications, the final design for the chassis frame was made. The chassis frame consisted of different shapes of beam such as angle beam, square beam and plate all made of steel. From the calculation of the material mass by using Solid Works, the total weight of the final chassis frame was 80.12 kg including the T-joint. This satisfies the specification provided for the design. High mass of chassis frame actually helps to lower the position of the center of the mass which provides stability to the robot while in motion. 3D model of the completed chassis frame and additional properties of the chassis frame as provided in Solid Works software is shown in figure 34.

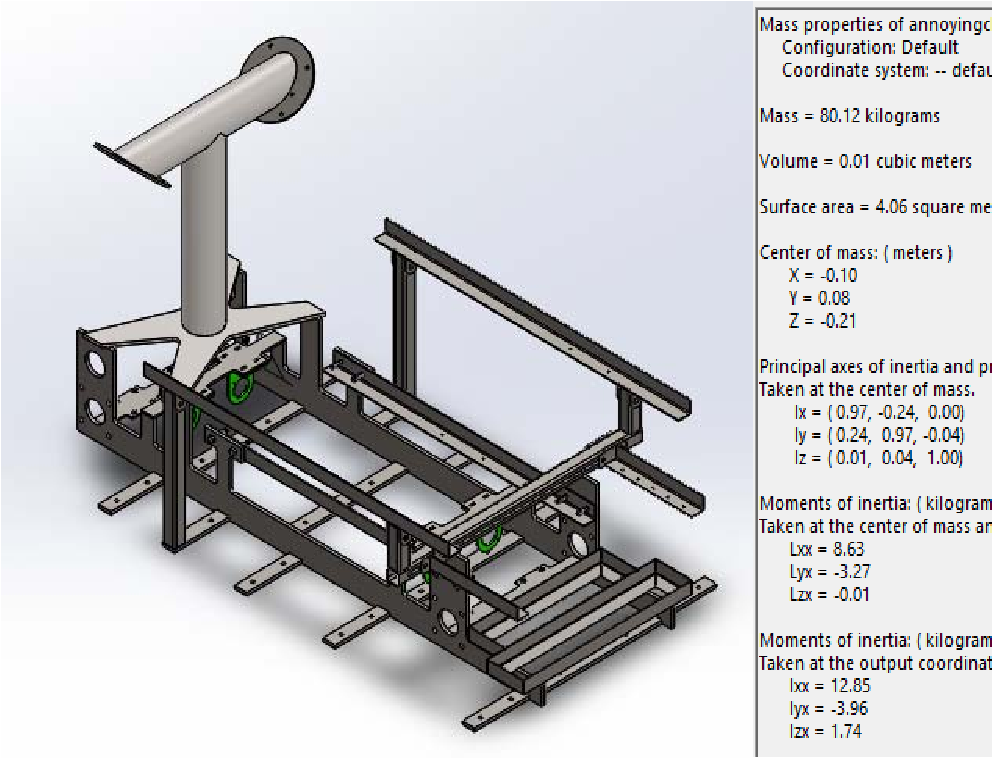


Figure 34. 3D- model of a complete chassis frame and its property.

After final design, all of the components were assembled in Solid Works to check out its center of mass and to get the overview of the robot. This design was presented in the project meeting and it was fully approved. This had several advantages over the previous design which are summarized here.

1. This design consists of less components, and same part has more functionality in this design.
2. Most of the components comprise of the steel plate.
3. Two layer design provides more space for electronic components and other additional components that might be necessary to be added in the future.
4. In this design, the assembly and disassembly process required during maintenance is much easier.
5. The design provides more tolerance freedom while mounting motor and bevel gear.
6. This design also consists of less welded joints and more use of nuts and bolts which also creates more space in the design.

The completed 3D model of the robot chassis frame with all external connected components are provided in figure 35 and the table 5 immediately following this figure summarizes the main general results of the chassis frame design.

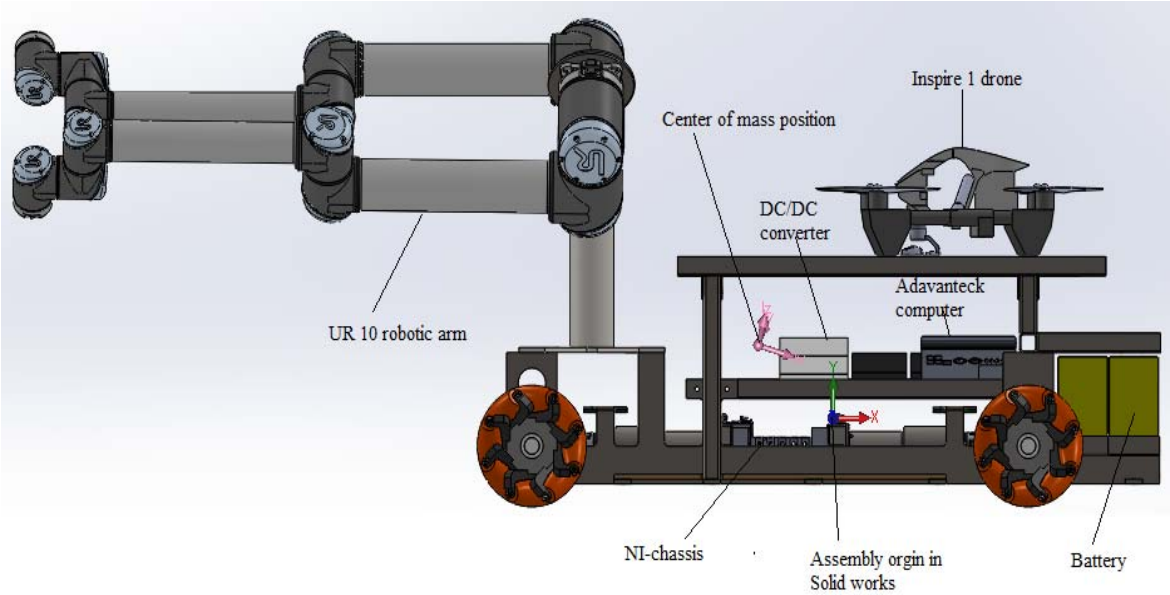


Figure 35. Complete robot structure with respective components.

Table 6. General result for chassis frame design.

Speciation	**Result and process**
Position of center of mass	528mm back from front wheel center, 345 mm toward center from front right wheel, 338mm from ground level.
Total chassis frame mass	Around 80.50Kg from Solid-works mass calculation.
Overall robot dimension	1597 length and 800 mm width and 950mm height.
Manufacturing and joining process	Welding, machining and cutting
Overall robot weight	Around 300Kg

3.4 Execution phase

This execution phase is the start of the manufacturing process that is determined by the shape, size and other dimension requirements of the design. Manufacturing involves different series of related operations. (Rajput, 2007, p. 1.) The scope of this thesis, however, was only limited to the design of the chassis, selection of the material, and the quality assurance of the chosen material through finite element analysis. Manufacturing process might also consist of several other operations including the process planning, inventory control and other company related decisions which are beyond the scope of this thesis.

3.4.1 Prototype manufacturing

Prototype is an experimental model. All of the manufacturing drawing made are provided in the (appendix I). Besides this, during the design for assembly process, manufacturing and assembly problems that might appear were identified already at the early design stage. This ensures that all the factors that can affect the final outputs are identified early in the design stage. This time given in the early design stage saves wasted time spent in repeated redesign. (Xie, 2015, p. 3.)

Design for assembly (DFA) is usually used either for assembly analysis or to provide as a guide for assembly design. The former relates to identifying all different factors that can affect the assembly process at the beginning of the product design and providing with suggestions. The latter relates to collecting assembly expert opinions and using them as design guides. Both of these methods can help engineers to determine an appropriate design plan. (Xie, 2015, p. 3.)The type of policy regarding the design plan is obviously the choice of the company involved.

General manufacturing operations includes cutting, machining and joining process. The cutting process is used during manufacturing to produce the final shape of a component. As the chassis design includes 10mm plate, the recommended cutting process are laser and water jet cutting. Machining quite simply is a cheap form of cutting process, involving several other process such as drilling and milling to produce the required dimensions and tolerance of the components required. Joining includes welding, adhesive bonding and mechanical fastening and an important manufacturing process as well.

3.4.2 Validating and system configuration

This process occurs when the manufacturing company approves the prototype of the chassis frame. However, validation of the system configuration can also be done through 3D modelling approach and related final element analysis. The description of how the specifications were made for this design project were presented in section 3.2.1 and will be discussed further in chapter 4.

4 ANALYSIS OF A CHASSIS FRAME

The model for the chassis frame was produced by using Solid Works software and was transferred to FEMAP software in a form of parabolic file for analysis. The process involved in the analysis of the chassis frame design is illustrated in figure 36.

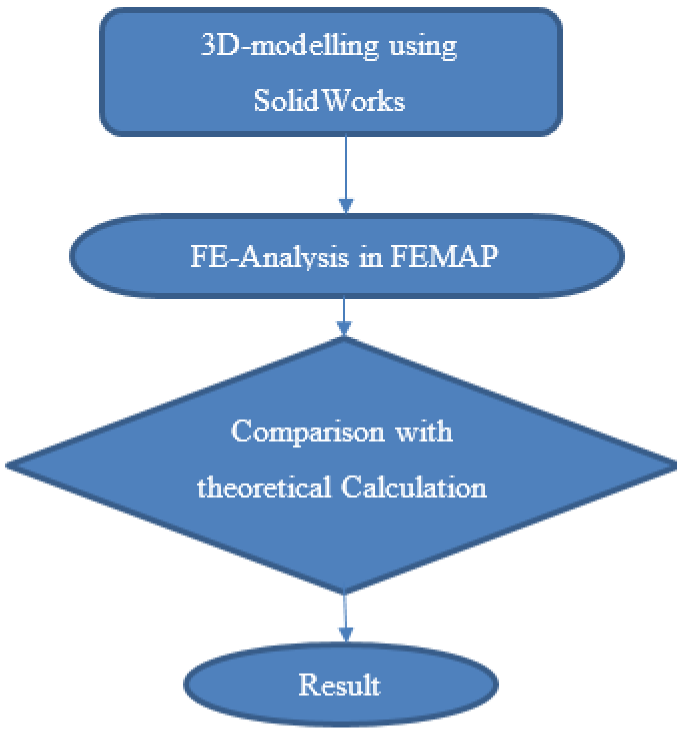


Figure 36. Flow chart for analysis process.

The main challenge of the analysis process is to transfer the computable model in the finite element software. Besides this, more importantly, quality assurance methods should also be used to verify the simulation result. These can be verified either by-hand calculation or by using the standard measured process. This is also a critical component of the finite element analysis process. Without quality assurance in place, modeling and input errors can lead to wrong conclusions and a misguided design. This can lead to fatal error leading to unsafe products in real life.

4.1 Static analysis

The objective of static analysis is to determine the effects on structure by steady load. In this case, the main static load is the result of the net weight of the robot weight and the payload. The weight of the components act on the center of gravity points of the chassis. In order to conduct static analysis, load case are bending, torsion or combination of both. All of these effects are elaborated in this section.

4.1.1 Bending load analysis

In an equilibrium condition, body weight and pay load act downwards and the mechanism wheel reaction force acts upwards. While conducting bending load analysis, the structure is assumed to be at zero inclination. In order to conduct bending load analysis for the chassis frame, the model for the chassis frame was imported into FEMAP. In order to conduct bending analysis, the process followed are as follows:

Defining material properties: The first step considered in FEMAP analysis was to define the material properties. The material properties of steel which acts as inputs in FEMAP analysis are summarized in table (as table 6).

Table 7. Material property define in FEMAP

Stiffness and density	**FEMAP input**	**SI unit value**
Young modulus,(E)	210000 MPa	$200*10^9$ pa
Shear Modulus,(G)	76000 MPa	$76*10^9$ pa
Poisson ratio,	0.3 (unit less)	0.3 (unit less)
Mass density	$8.65*10^{-9}$ Tones/mm^3	7850 Kg/m^3

Loading: Load were applied as weight of the robot component in their expected places in the chassis frame. Figure 37 shows how different weights acts as forces and act downward. For T-joint supports and motor mounting place, moment is also applied.

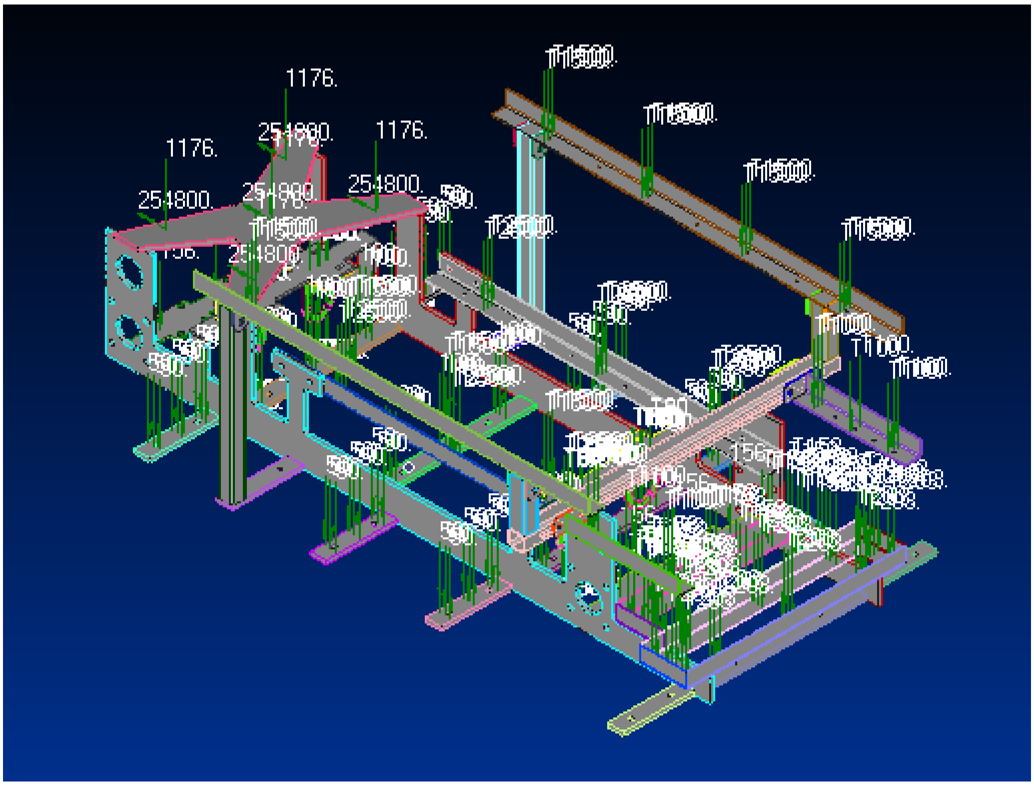


Figure 37. Loading on the chassis frame.

Boundary condition: For the chassis frame, the boundary condition area are the bearing mounting holes. For all of these mounting holes, fixed constraints were applied as shown in figure 38.

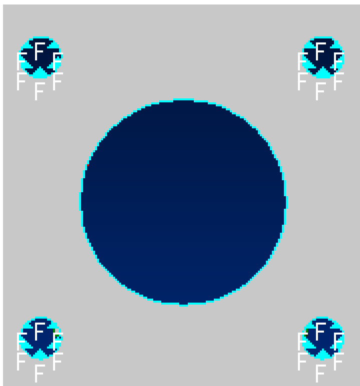


Figure 38. Boundary condition constrain applied on mounting hole.

Meshing: For meshing of the chassis frame, a specific form of element called linear tetrahedral solid element were used. According to Kattan (2008, p.337), It can be defined as “three dimensional finite element consisting of both local and global coordinates.” It is a linear function consisting of different stiffness properties such as Young’s Modulus and

Poisson ratio. (Kattan, 2008, p. 337.)The meshing process of the chassis frame in FEMAP is shown in figure 39.

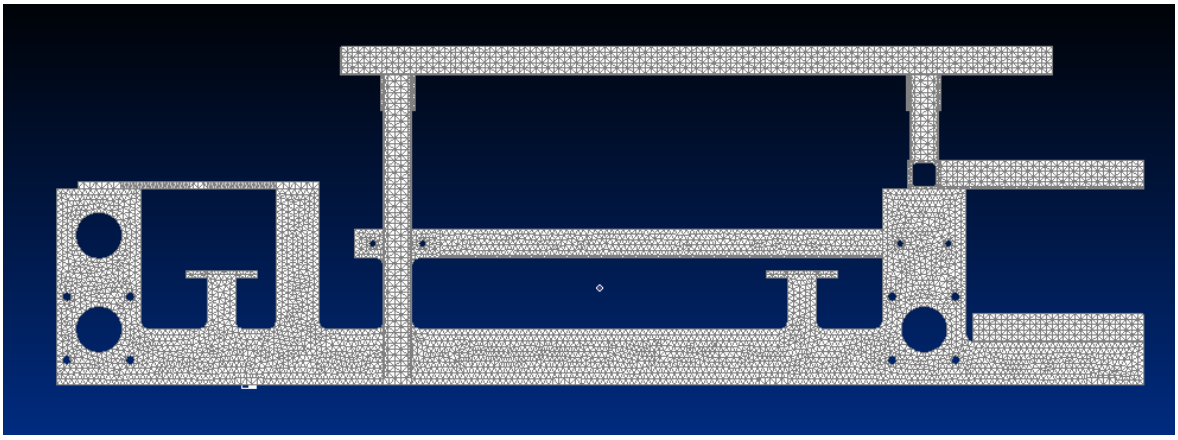


Figure 39. Linear tetrahedral (solid) element meshing in chassis frame.

FEMAP Result:

After running the FEMAP analysis, the results show that the maximum deflection is 0.512mm, which lies on the base of the fuse part as shown in figure 40.

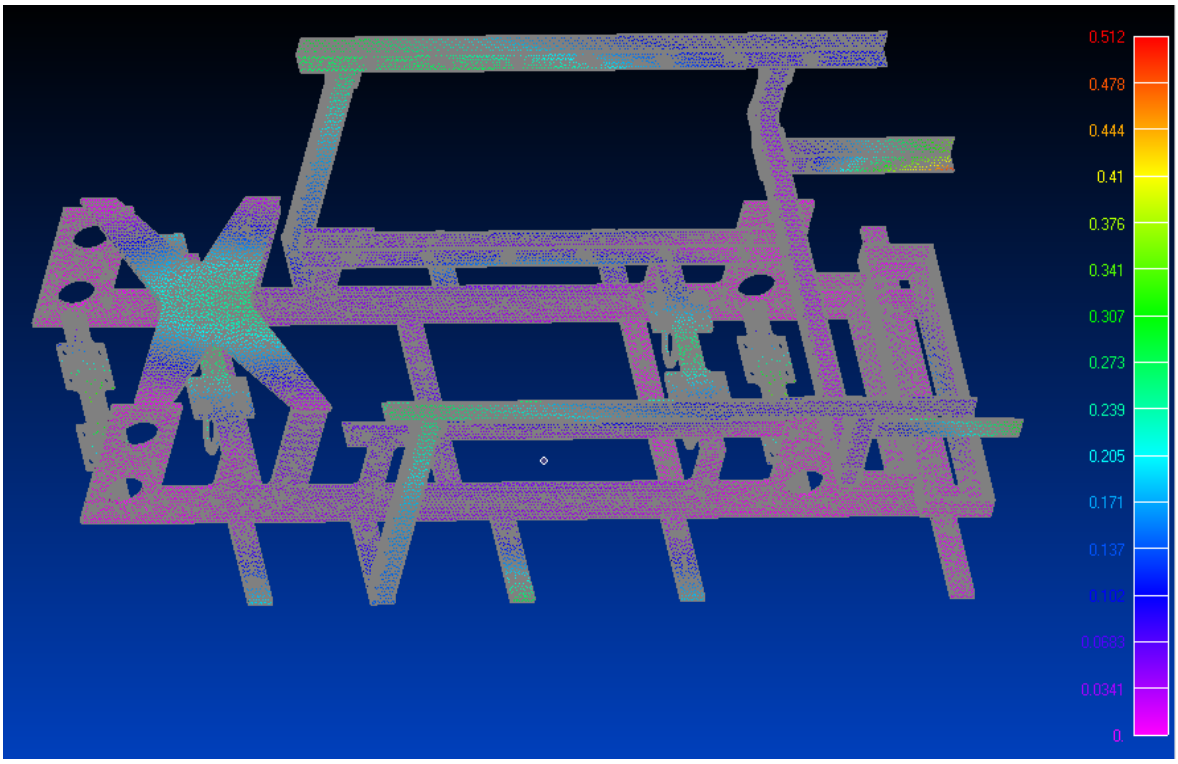


Figure 40. Deflection on chassis frame.

After preliminary FEMAP analysis, von mises stress analysis is conducted. The results show that the maximum stress is 33.53 MPa which is also illustrated in figure 41. The position of the maximum von mises stress lies on the T-joint base and bevel gear support connected with the plate beam.

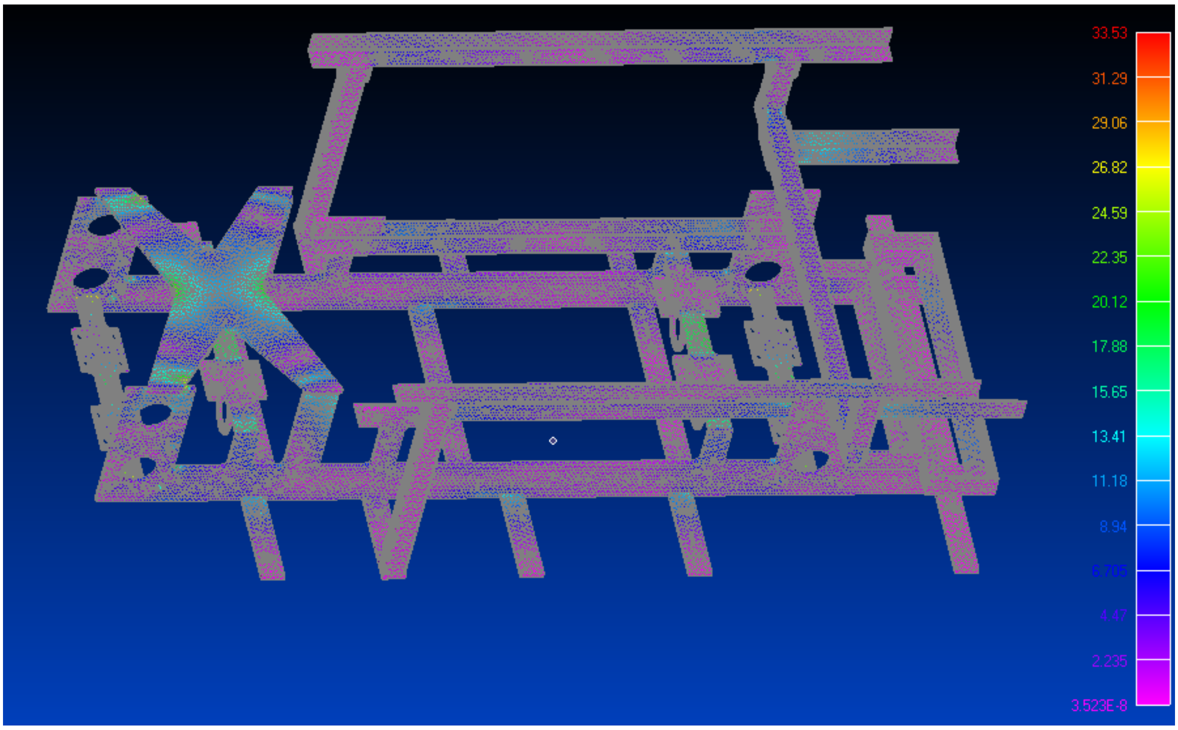


Figure 41. Von misses stress result from FEMAP.

After this constrain force analysis was simulated and the resultant reaction force is illustrated in figure 42. The maximum constrain force occurs on the front mounting hole which is 279N and for the rear mounting hole, constrain force is 130 N.

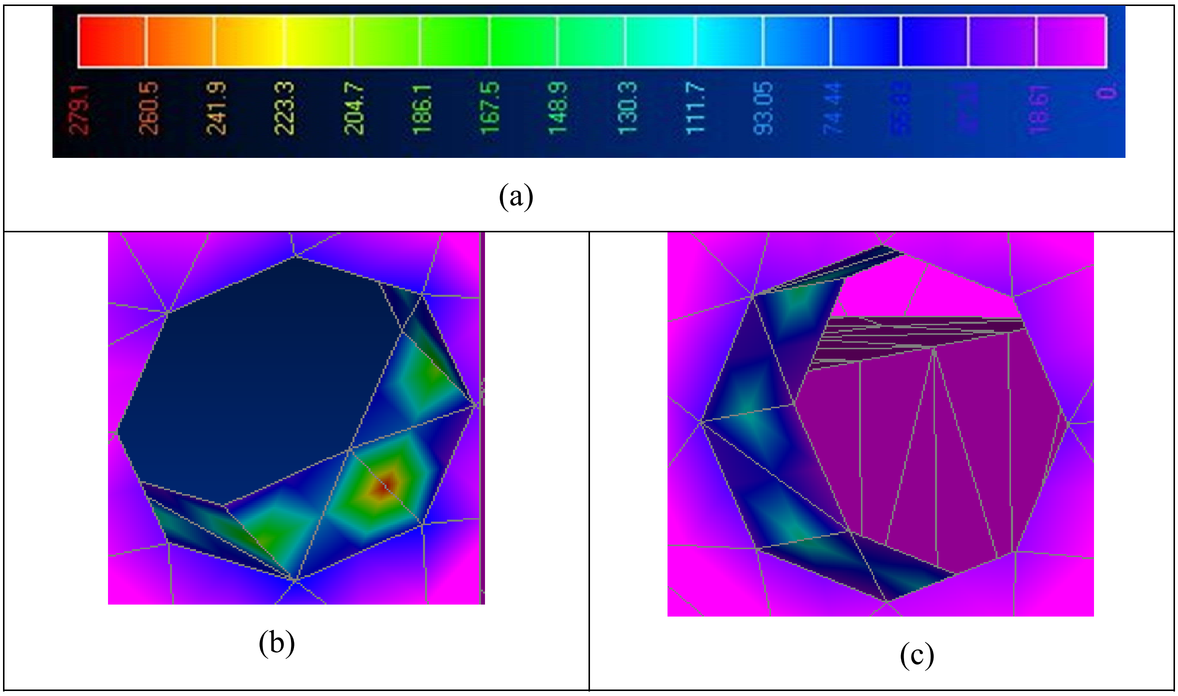


Figure 42. (a) Reaction force range in Newton (b) Bolt reaction force range in front hole (c) Rear bolt reaction force in rear hole.

Quality assurance of the bending forces and stress

After previous processes, it is also necessary to calculate the stress and deflection load reaction force by using proper mechanics calculation. Earlier in table 7 different weights were already presented.

Table 8. Robot weight table for analytical analysis.

Total weight of the robot and payload		
	kg	**N**
Pay load	40	392
Net robot weight	300	2940
Gross robot weight (GRW)	340	3332

It is assumed that the only beam considered is simply support beam and the gross robot weight acts on the center of mass that was derived already from frame design in Solid Works.

Analytic calculation for reaction force: It is necessary to determine the static loads in the form of reaction force exerted on the bolt mounting position. The free body diagram is shown in figure 43.

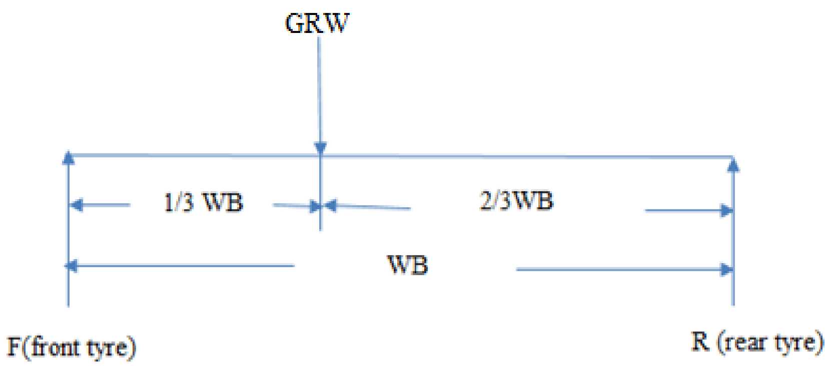


Figure 43. Free body diagram for robot plate beam.

The numerical representation of the free body diagram is shown in figure 44 (a) and in figure 44 (b) the reaction force is divided equally on each wheel part.

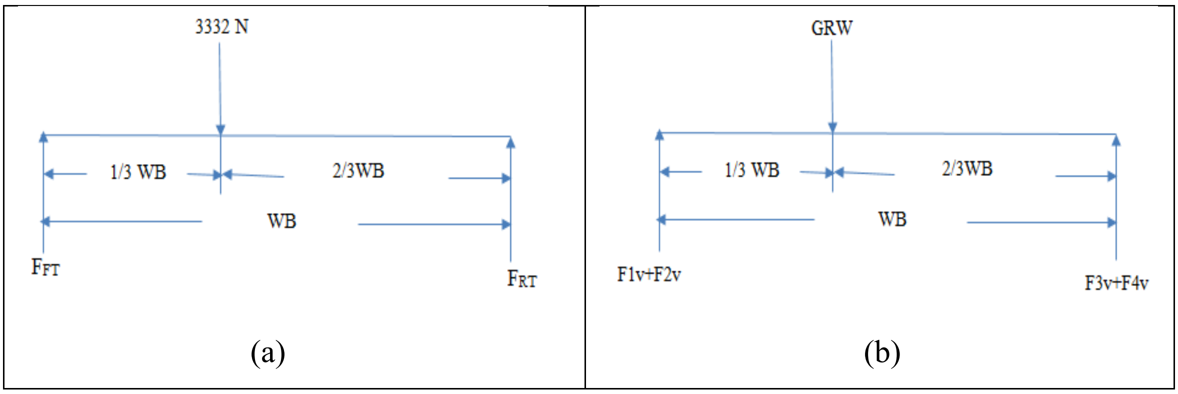


Figure 44. Numerical representation with free body diagram for robot.

In the figure, WB represents the wheel base and its length is 1160mm,

2/3WB =773.33mm and

1/3WB =386.67mm

According to the equilibrium condition, on a free body diagram,

Taking the moment from front tyre i.e.

$$\sum M_{FT} = 0 \tag{2}$$

By using equation 2 and putting the respective values derived from the numerical representation of the free body diagram (see figure 44); it can be calculated that:

$F_{RT} * 1160 = 3332 * 386.67$

$F_{RT} = 1110.68N$

Where,

F_{RT}= is total force in Rear tyre.

Taking moment at rear tyre i.e.

$$\sum M_{RT} = 0 \quad (3)$$

Similarly, by using equation 3 and putting the respective values derived from the numerical representation of the free body diagram (see figure 44); it can be calculated that:

$F_{FT} * 1160 = 3332 * 773.33$

$F_{FT} = 2221.32N$

Where,

F_{FT}= is total force in Front tyre.

For front plate connection load, at each bolt F_{FT}/ number of bolts

So, F_{FT} at each bolt =2221.32/8= 277.66N

For rear plate connection load at each bolt F_{RT}/number of bolts

So F_{RT} at each bolt =1110.68/8= 138.835N

Analytic calculation from stress:

Height (h) of the plate beam as shown in figure 45 is assumed to be 130 mm and width (b) is 10 mm. As it is a solid, the moment of inertia of this beam is calculated as solid rectangle shape.

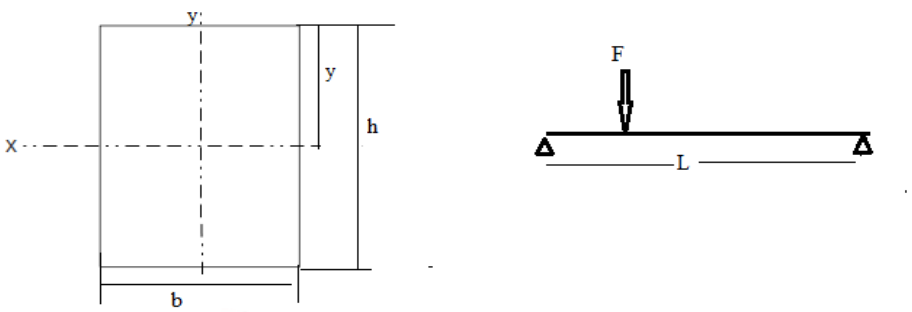


Figure 45. Beam cross section and its length and acting force.

The formula for the moment of inertia for solid rectangle cross is given in equation (Yong & Budynas, 2011, p. 802).

$$I_x = b * h^3/12 \quad (4)$$

Where,

I_x= moment of inertia about the x-axis.

b= the width of beam and its value is10 mm.

h= is the averaged assumed height and its value is 130mm

By using equation 4, moment of inertia is derived to be 1830833.333mm^4.

The formula for the maximum bending stress is given in equation (Yong et al., 2011, p. 802):

$$\sigma_{max} = y * (F * L/4)/I_x \quad (5)$$

Where,

σ_{max}= maximum stress on the beam.

F= is total robot gross weight, the value of which is 3332N.

L= is the base width of the robot, the value of which is 1160mm.

y= is the perpendicular distance from neutral axis and its distance is 65mm.

By using formula 5, the maximum bending stress is 34.30MPa.

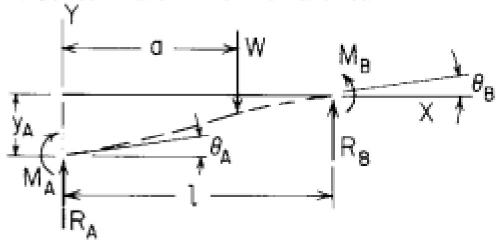
Analytic Calculation for deflection: Maximum possible deflection on beam from general chart is shown in figure 46. Formula for maximum deflection on supported beam is given in equation:

$$y_{max} = FL^3/(48 * E * I_x) \quad (6)$$

y_{max} = is the deflection of a beam

By using equation 6, beam deflection derived is 0.28181mm.

1. Concentrated intermediate load



(a)

$$R_A = \frac{W}{l}(l - a) \qquad M_A = 0$$

$$\theta_A = \frac{-Wa}{6EIl}(2l - a)(l - a) \qquad y_A = 0$$

$$R_B = \frac{Wa}{l} \qquad M_B = 0$$

$$\theta_B = \frac{Wa}{6EIl}(l^2 - a^2) \qquad y_B = 0$$

(b)

Max $M = R_A a$ at $x = a$; max possible value $= \frac{Wl}{4}$ when $a = \frac{l}{2}$

Max $y = \frac{-Wa}{3EIl}\left(\frac{l^2 - a^2}{3}\right)^{3/2}$ at $x = l - \left(\frac{l^2 - a^2}{3}\right)^{1/2}$ when $a < \frac{l}{2}$; max possible value $= \frac{-Wl^3}{48EI}$ at $x = \frac{l}{2}$ when $a = \frac{l}{2}$

Max $\theta = \theta_A$ when $a < \frac{l}{2}$; max possible value $= -0.0642\frac{Wl^2}{EI}$ when $a = 0.423l$

(c)

Figure 46. Deflection formula for elastic straight beams (a) end restraints (b) boundary values (c) selection criteria for moment and deformations (Yong et al., 2011, p. 190).

By using equation 6, the beam deflection derived was 0.28181mm. Once this is known, the bending stiffness of a beam can be calculated by using the following equation. (Murali, Subramanyam, & Dulam, 2013, p. 4.)

$$\text{Bending stiffness} = \frac{\textbf{total applied load}}{\textbf{deflection at point of application of load}} \qquad (7)$$

By using the formula for bending stiffness, the value for beam derived is 11823.55N/mm.

The analytical results and the FEMAP results are shown in table 8. The comparison table shows that FEMAP analysis corresponds to the analytical solution. The discrepancies can be explained because the analysis is done on complete structure whereas the analytical solution is only conducted for a particular component.

Table 9. Comparison of analytical result and FEMAP.

Name	FEMAP result	Analytical result
Reaction force in front mounting hole	279.1 MPa	277.66N
Reaction force in rear mounting hole	130.3MPa	138.835N
Bending stress	33.53MPa (Von misses stress)	34.30MPa
Deflection	0.518 (it on fuse support part)	0.28 (it on plate beam)

4.1.2 Torsional stiffness

The basic premise of torsional stiffness is that when asymmetric forces acts on a body, the body tends to twist. This can either happen by roughness of the road or in the specific case of the robot manipulator, if the arm move in the same direction, the frame can be subjected to torsion. The torsional stiffness of the chassis were calculated by using the results from finite element analysis.

Finite element method:

The chassis frame was modeled as mesh in FEMAP and analysis was conducted to check for torsional stiffness. To analyze the torsional stiffness, the front wheel reaction force derived from the calculation related to bending was applied in the mounting point in the opposite direction as shown in figure 47. The rear mounting part was fixed as constrain. The applied value of the force F1 and F2 were 1110, 66N. For the meshing process, the solid element used was tetrahedral and the material considered was that of steel. The results derived after the simulation process are presented in figure 48. From the front, it can be seen that the front part of the robot frame is twisted relative to rear. From the result it can be seen that the maximum deflection is 1.941 mm acting downwards.

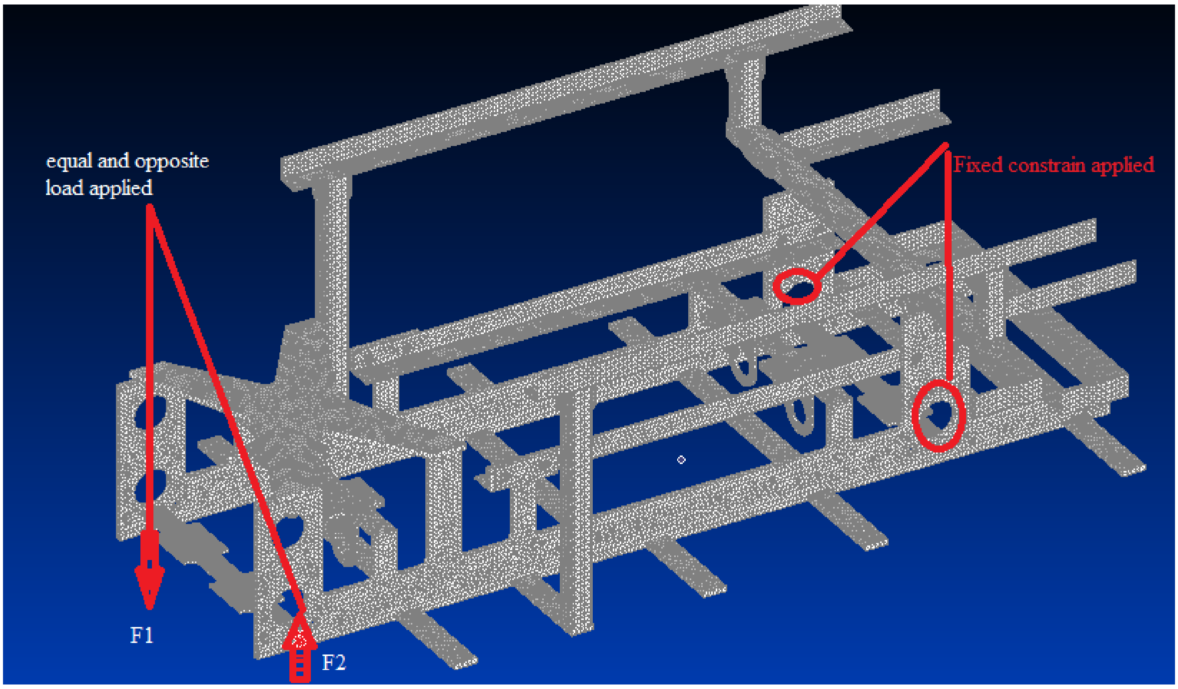


Figure 47. Applied force and constrain in torsional stiffness.

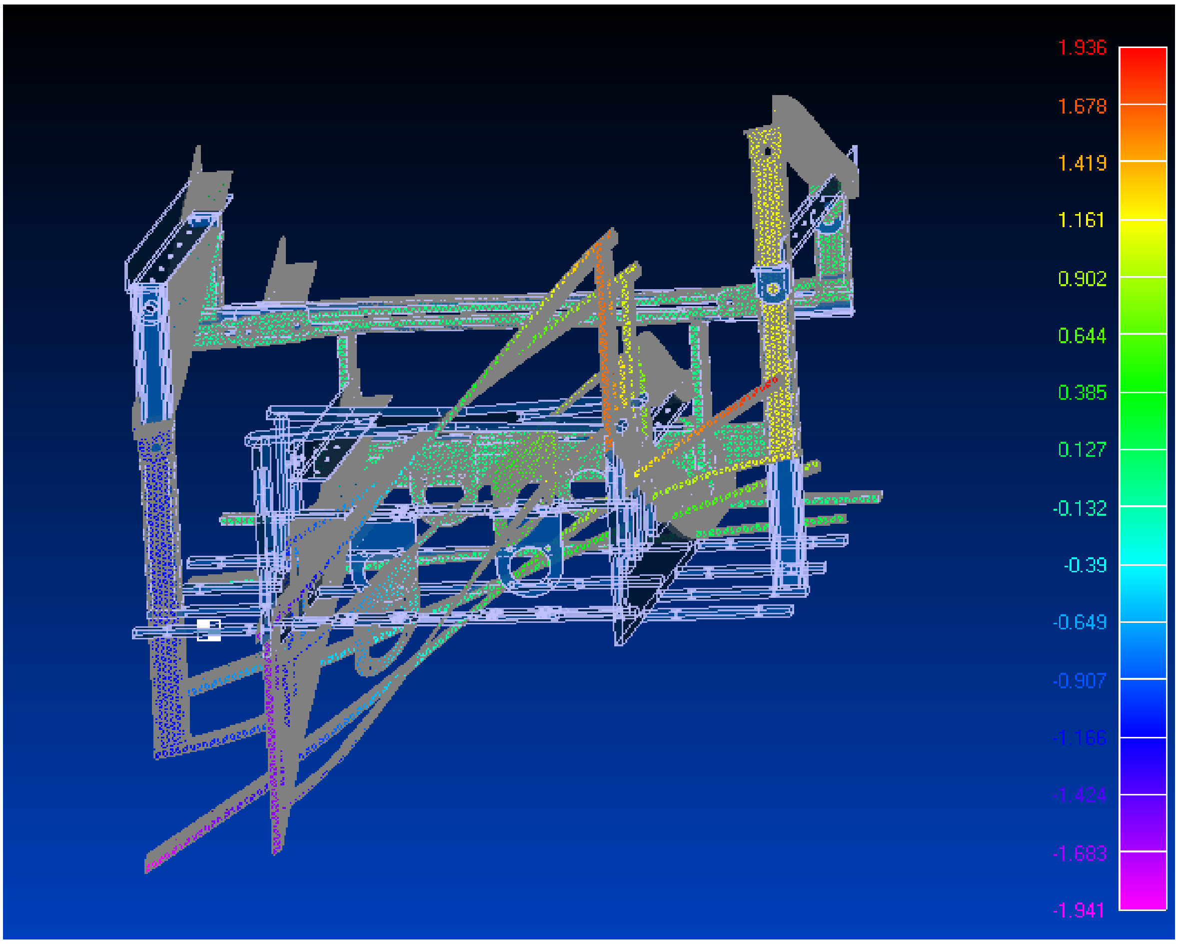


Figure 48. Deflection from simulating result.

In simulation method, the equation used to define torsional stiffness (K_T) are given by equations (Tebby, Esmailzadeh, & Barari, 2011, p. 68):

$$K_T = \frac{T}{\varphi} = F2 * \text{track width}/\ (\varphi_d + \varphi_p) \quad (8)$$

Where,

$$\varphi_d = \tan^{-1}(v_d/\ (\text{trackwidth}/2)) \quad (9)$$

$$\varphi_p = \tan^{-1}(v_p/\ (\text{trackwidth}/2)) \quad (10)$$

T= is the torque and its unit is Nmm.

φ= is angle of the twist

v_d= is the deflection in right and its value is 1.936 mm from the simulation results.

v_p= is the deflection in left and its value is 1.941 mm downward from simulation results.

From the calculations, the value derived for φ_d and φ_p is 0.33° and 0.33° respectively. Torsional stiffness value for K_T is 3382484.848Nmm/degree. Generally, for a medium type of chassis frame for warehouse heavy duty function, the torsional stiffness is greater or equal to 2000000 Nmm/degree. (Chaojie, 2013, p. 9.)Considering this as a standard, the torsional value of the designed chassis is quite high. So, it can be claimed that the design is acceptable.

Analytic calculation for torsional stiffness:

Since, chassis has a multiple and complex cross sectional geometry it is very hard to define beforehand how this geometry will be deformed while twisted. It is difficult and tedious process to determine torsional stiffness based on such geometry. Therefore this is not considered in this report. The analytical method would be to determine the torsional stiffness only based on the geometry but this can be costly as large number of long calculations are needed to be performed. In the industrial context, the considered FEA-based method is a more practical approach (Tebby et al., 2011, pp. 68-74.)

4.1.3 Combining bending and torsional stress

In a real life situation, bending and gravitational force are always present and without it torsion cannot exist. Therefore, it is necessary to consider both of these scenarios together.

(Happian-smith, 2001, p. 126.) To calculate considering this situation, one of the wheel is considered to rise on a bump and the other wheel goes off so that all the load goes to another adjacent wheel.

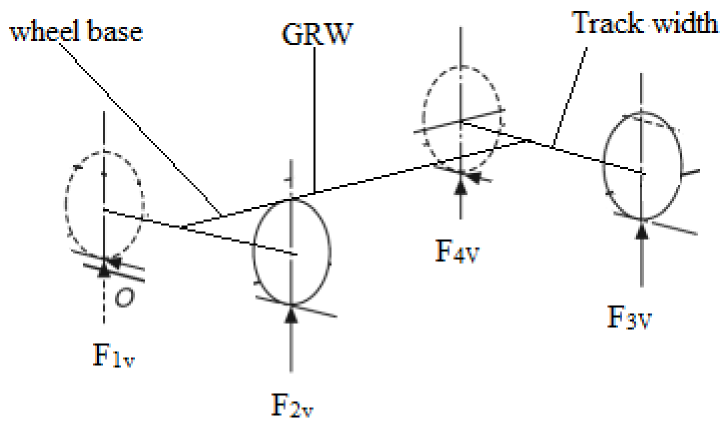


Figure 49. Combining bending and torsion load.

If the front right wheel is assumed to be on a bump then mathematically the reaction force is zero. This can be considered as right ramp loading if following conditions is fulfilled:

$F_{1v} = 0$ N

From this condition, other relationships can also be established, as below:

$F_{FT} = F1v + F2v$

$F_{FT} = F_{2v} = 2221.32$ N

Where,

F_{1V} =Force in left front tyre [N]

F_{2V}= Force in left front tyre [N]

Taking moment at a rear right wheel point i.e.

$$(\sum M\ F_{4V} = 0) \qquad (11)$$

While solving equation 11,

$F_{3v} \times TW = (GRW * TW/2) + (TW* F_{2v})$

$F_{3V} *670 = (3332 *670/2) + (2221.32)* 670$

$F_{3V} \times 670 =1116220+1488284.4$

F_{3V}=2604504.4/670=3887.32N

Taking moment at a rear left tire point i.e.

$$(\sum M\ F_{3v} = 0) \qquad (12)$$

While solving equation 12,

$$F_{4v} \times TW = (GRW * TW/2)$$

$$F_{4v} = 1666N$$

F_{3V} =Force in right rear tyre [N]

F_{4V}= Force in left rear tyre [N]

By applying these forces in the model and meshing, the resulting stress derived from FEMAP analysis was already presented in figure 50.

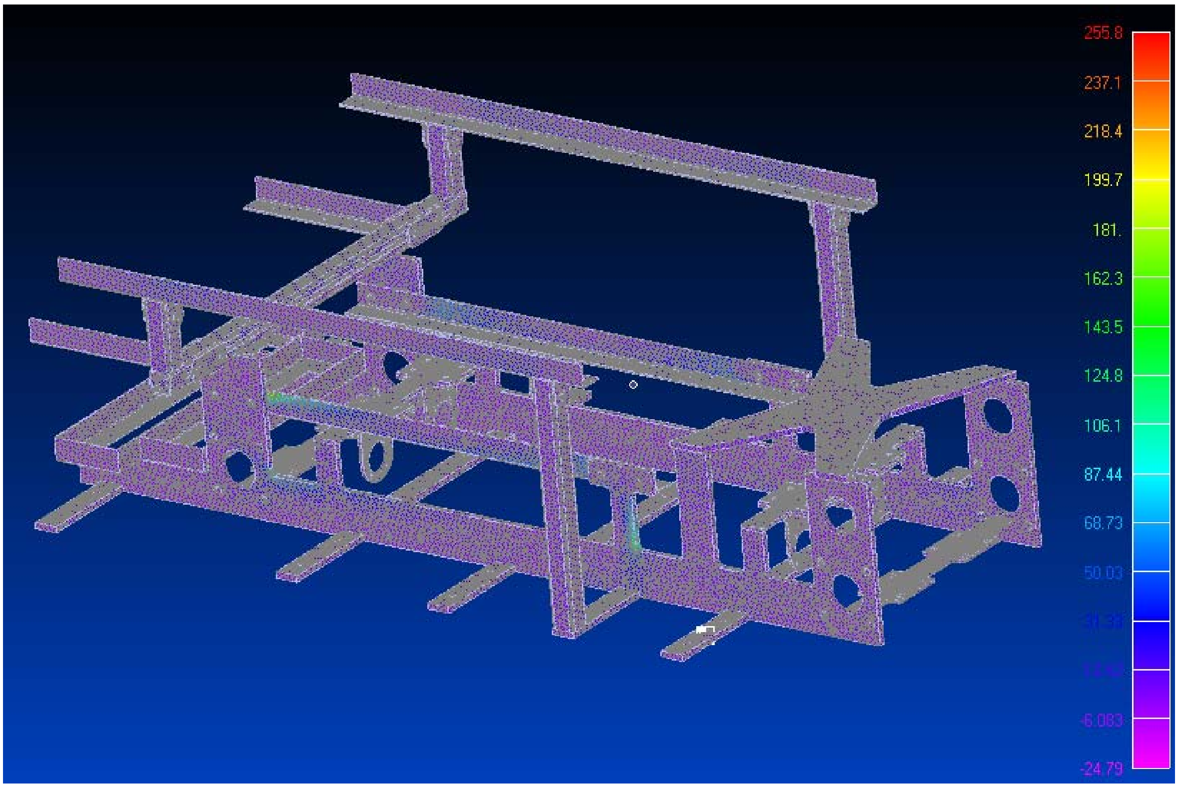
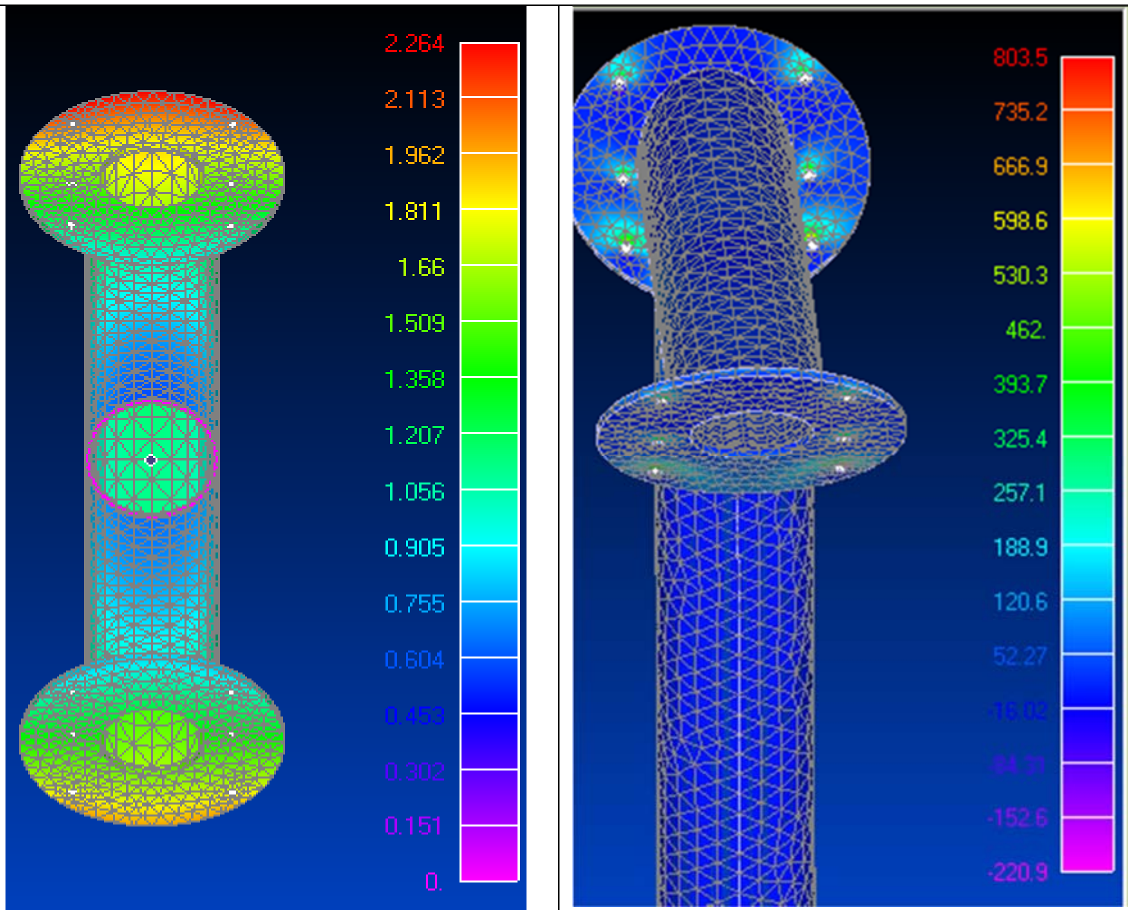


Figure 50. Result derived from simulation by combining loadings.

The maximum principle stress derived from FEMAP analysis is 255.8MPa, which is still acceptable for Optim 900QC steel. Generally other parts in the chassis frame have lower stress. When the loadings are combined, the chassis frame suffers maximum stress. If the chassis frame is proven sufficient for the combined load, it can be considered to be capable of dealing with other loads as well.

4.1.4 T-joint analysis

The Model T-joint is one of the critical component of the design and it is welded to the t-joint base. In order to mount the UR 10 robotic arm, 6 mm plate is welded at an angle of 45 degrees. All of the weight and moments results from placing the robot arm in place on a mounted plate hole position with the total weight of 400 N and moment of 130000Nmm created by 10kg payload. Resulting simulation for mounting plate of 6mm thickness is given in figure 51.

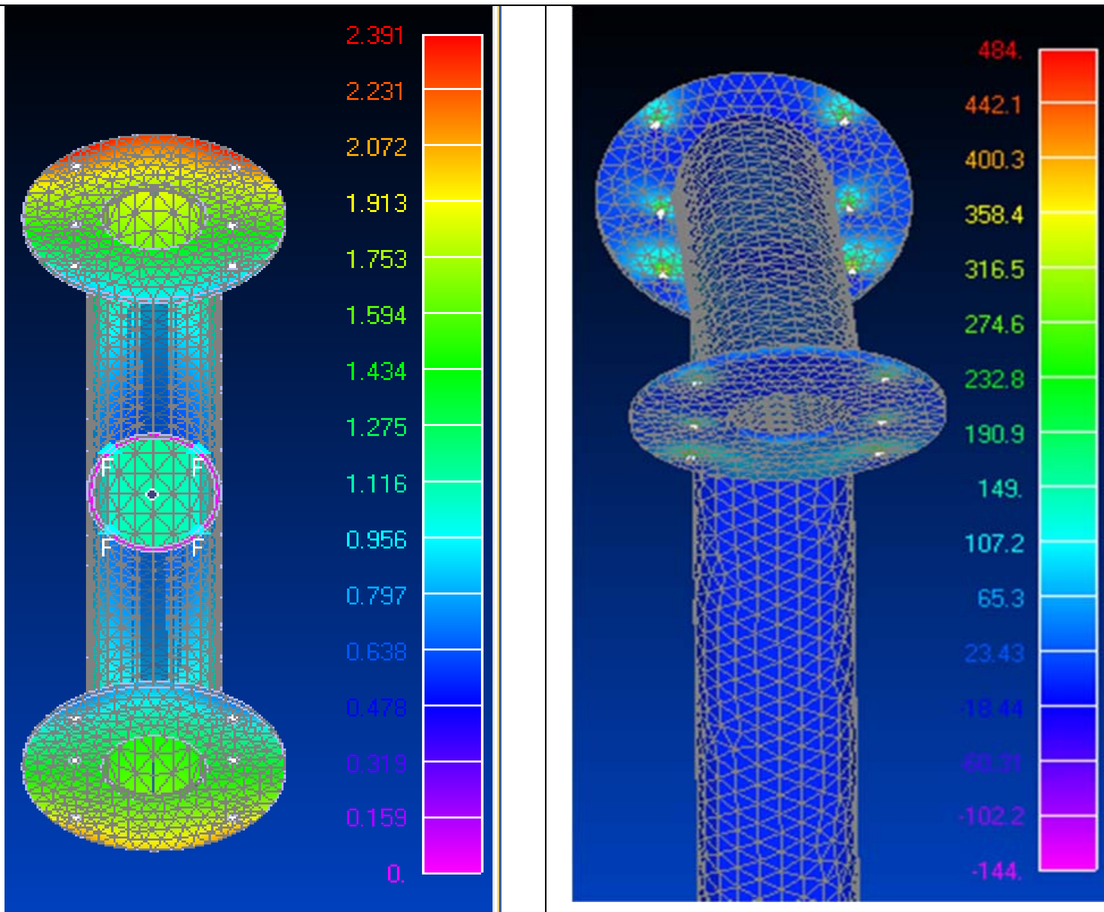


(a) (b)

Figure 51. Analysis result for T-joint with 6mm plate (a) Deflection result (b) Maximum principle stress.

From the simulated results, it can be clearly seen that the stress on 6mm plate is around 803MPa, which is normally too high and deflection on plate is around 2.264mm. For dynamic cases, in worst case scenarios, the allowable stress is equal or less than 67% of the yield stress of a material. The material chosen for plate is Optim 900 QC whose yield strength is 900Mpa. This T- joint is assumed to be in the worst case scenario so the plate stress should be less than 603MPa. This means that this 6 mm plate is not suitable for holding the robot arm.

As a result, 8mm plate was considered and again analysis was simulated. From this simulation, the maximum principle stress derived was 484 MPa which is far less that worst condition allowable stress. Analysis results for T-joint with 8 mm mounting plate are shown in figure 52.



(a) (b)

Figure 52. Analysis result for T-joint with 8 mm plate (a) Deflection result (b) Maximum principle stress.

The deflection derived is 2.391 mm and the diameter of the mounting plate is 200 mm. Considering the material properties, the allowable elongation is 8%. By calculation, the elongation with plate diameter is just 1.12 %, which is in the acceptable range. Generally stress in pipe is less than 320MPa which is less than chosen pipe yield stress. Pipe property and dimension is given in appendix III, 3. It is recommended to consider 8mm thickness for a robot arm mounting plate.

4.2 Dynamic Analysis

The frame is the main backbone of the robot and it is connected to the power train and suspension. Therefore, the robot frame is also subjected to dynamic and cycling loading. Dynamic analysis helps to eliminate excessive vibrations and dynamic stress. With this analysis it is possible to determine operational deflection shape and conduct model analysis, response analysis and determine dynamic stress. Even though dynamic analysis is beyond the scope of this thesis, some issues related to the selection criteria for allowable stress are discussed in this section.

In worst dynamic cases, allowable stress is equal or less than 67% of the yield stress of a material. For bending case, maximum stress is shown in equation (Happian-smith, 2001, p. 105):

$$\text{Stress due to static load} * \text{Dynamic factor} \leq \frac{2}{3} * \text{yield stress} \qquad (13)$$

The value of the dynamic factor is set empirically. (Vehicle Safety Research Integration Symposium, 1973, p. 10.) It is simply defined as the ratio of the difference between tractive force and air resistance to vehicle over the force of gravity acting on it (The free dictionary by farlex, 2010). More precisely, it is given in equation:

$$\text{Dynamic factor} = (\text{Tractive force } - \text{air resistance })/\text{force of gravity} \quad (14)$$

From the equation, it is quite apparent that at this stage of the project it is impossible to determine the dynamic factor.

In order to determine the dynamic factor, the chosen material and the yield stress value were replaced. To construct the chassis, Optim 900 QC steel was used and its yield strength is 900MPa. Besides that, maximum stress derived during static load analysis is 255.8MPa during the combined load case for torsion and bending. By using equation 11 and 12, dynamic factor derived is 2.35. Considering that forklift has similar functionality to indoor robot with mechanical arms, forklift could be used as standard for comparison in the absence of other official standards. When the forklift has solid wheel, the dynamic factor is considered to be 2 and in the case of pneumatic wheel it is considered to be 1.40. This factor accounts for inertial effects due to acceleration and deceleration caused by hoisted load. (Nikolaos, 2008, p. 29.) Assuming similar functionalities, the dynamic factor for robot can be considered as over the acceptable range as it is 2.35 while also including solid Omni wheel.

5 RESULT AND DISCUSSION

In this project, chassis frame model and manufacturing drawings were made in Solid-Works software. Model figures were presented in chapter 3, and manufacturing drawings are presented in (appendix I.) During the process, material selected is steel, because its high weight gives stability and act as counterbalance for manipulator by lowering its center of mass. Selected material property and dimension are given in (appendix III.)

Model chassis frame have less parts, low center of mass position, is symmetric, and the center of mass lies inside wheel base. Besides that, it has assembling and dissembling properties, is stiffer and has much more space. Generally it fulfills all design requirements of the project.

Chassis structure analysis was done by tetrahedral linear solid mesh in FEMAP software. During the analysis steel properties were used. After simulation process, the results were verified with quality assurance and results were satisfying. General results are presented in table 9.

Table 10. Summary of the result.

Constrain	**Parameters**
Overall chassis dimension	1597*800*950
Chassis mass	80.50Kg
Overall robot center of position (all component included)	528mm back from front wheel center, 345 mm toward center from front right wheel, 338mm from ground level.
Maximum deflection chassis frame	0.512mm
Bending stiffness of plate beam	11823.56N/mm.
Maximum stress in bending case	33.53MPa
Maximum deflection torsional case	1.941mm

Table 11. Continues. Summary of the result.

Constrain	**Parameters**
Torsional stiffness	3382484.848Nmm/degree
Maximum principle stress in combined load case	255.8MPa
Constrain	**Parameters**
Dynamic factor for robot frame	2.35
Maximum stress in T-joint	484MPa
Maximum deflection on T-joint	2.264mm

While the analysis for torsional load was conducted, the load was applied in the vertical direction but in reality it can apply in any direction or angle. As a result, the stress might vary depending upon the method of analysis. The maximum stress results in the chassis frame when the load are included in the combined form. Besides this, the stress at T-joint mounting plate is also high due to higher weight of the robot and the moment created by it.

If the specification did not include that UR10 needs to have shoulder like structure, the design could have been different. It is because this specification of the UR 10 largely determines the shape of the chassis. Besides this, if the quadcopter was not positioned on the robot body then the chassis frame could have been more compact and lighter as the UR 10 arm would shift in the middle and lighter material could have been used to balance it.

6 CONCLUSIONS

The main aim of this project was to design a robot chassis frame. The project for tele operated mobile robot for maintenance was carried out in laboratory of intelligent in a group. As a member of the project, design of chassis frame was done while other project members were focused on other components of the tele operated mobile robot. Chassis frame is a bearing structure of a vehicle which has to support all mechanical components and provide structure and stability.

Primarily, quantitative method was used to come up with appropriate design of the chassis frame. Various techniques and scientific principles were used to design a chassis frame such as symmetry, moment of inertia, mass distribution on frame etc. The virtual model for chassis frame was made by using Solid-Works software. Design principles were applied during the process throughout which consists of concept phase, development and execution phase. The design process was iterative in the sense that when the project specifications were not met, the design process again started from the early or concept phase. Several iterations were made until the project specifications were met completely.

At the end of the project, chassis frame of overall dimension 1597* 800*950 mm^3 was designed. Center of mass lies on 1/3 of the length from front wheel at height 338mm in the symmetry plane. Using material properties, mass of the total robot and center of mass were found. Further chassis frame dimensions along with constituent part drawings were made for the manufacturing company. It was the major objective of this thesis and a critical factor to determine the success of the project.

Beside this chassis frame, structural analysis was done in FEMAP which give the busting result for chassis design by taking into consideration stress and deflection on different kind of loading resembling real life case. Material selected was based on the strength required. On the basis of simulated result, selected material were verified. Chassis frame was designed which fulfilled the size, shape, material and manufacturing process requirements. Resulting design is expected to perform its intended function without failure.

As a suggestion for further research, additional fatigue analysis and proper dynamic analysis can be conducted to make the study more robust. If this thesis were to be developed further, it would be possible to include fatigue and dynamic analysis which would include model analysis, response analysis, and analysis of natural frequency, dynamic stress and operational deflection shape. Further steps would include undertaking of electrical and other control tests for the chassis frame.

REFERENCES

Aalto-University. 2009. [Aalto-University webpage] [Referred 11.9.2011] Available: http://autsys.aalto.fi/en/WorkPartner/Media

Ambot. 2015. Defense solutions [Ambot webpage]. [Referred 10.11.2015]. Available: http://www.ambot.com/defense.shtml

Ashby, F. M. 2005. Materials selection in Mechanical design. 3rd Edition. Oxford: Pergamon Press (Elsevier).

Bélanger-Barrette, M. 2015. [Robotiq company blog]. Updated April 2.2015. [Referred 11.11.2011]. Available: http://blog.robotiq.com/dirty-applications-using-universal-robots

Bibby, J. 2013. Mobility [web document]. Updated 31.5.2013. [Referred 3.11.2015]. Available: http://robonaut.jsc.nasa.gov/mobility/

Briggs, L. J., Gustafson, K. L. & Tillman, M. H. 1992. Instructional Design Principles and Applications. 2nd Ed. New Jersey: Educational Technology publications, Inc. 213 p.

Calvo, K. 2015. What you should know about the new DJI inspire1. [Web document] Updated 4.1.2015. [Referred 11.10.2015]. Available https://www.ercmarket.com: http://kikecalvoblog.com/2015/01/04/what-you-should-know-about-the-new-dji-inspire-1/

Chaojie, H. 2013 ACADEMIA [web database]. [Referred 21.10.2015].HEAVY-DUTY OMNI-DIRECTIONAL MECANUM MOBILE ROBOT. Available: https://www.academia.edu/8061343/HEAVY-DUTY_OMNI-DIRECTIONAL_MECANUM_MOBILE_ROBOT_PROJECT_IN_MECHATRONICS_ENGINEERING_Co-worker_Xie_Li_Supervisor

From, P. J., Gravdahl, J. T. & Pettersen, K. Y. 2014. Vehicle-Manipulator Systems Modeling for simulation, Analysis, and control. London: Springer-Verlag. 6 p.

Genta, G. & Lorenzo, M. 2009. The Automotive Chassis Volume2: System Design. Dordrecht, Netherland: springer science + Business media B.V. Pp. 103-110.

Genta, G., Morello, L., Cavallino, F. & Filtri, L. 2014. The Motor Car Past, Present and future New York: Springer. pp.15-16.

Gray, J. 2008. Lotus race. [Referred 11.12.2015]. Available: http://www.lotusracer.com/: http://www.lotusracer.com/index.php?section=49

Gregory, J. 2005. Materials selection for Mechanical design I [web document]. [Referred 11.11.2015]. 44 p. Available in PDF-file: http://ocw.mit.edu/courses/materials-science-and-engineering/3-080-economic-environmental-issues-in-materials-selection-fall-2005/lecture-notes/lec_ms1.pdf

Happian-smith, J. 2001. An introduction to Modern Vehicle Design. Oxford: Reed Educational and Professional Publishing Ltd. Pp. 137-143.

Heissing, B., & Erosy, M. 2011. Chassis Handbook Fundamentals, Driving Dynamics, Components, Mechatronic, Perspectives. Berlin: Vieweg+Teubner Verlag |Springer Fachmedien Wiesbaden GmbH 2011. Pp.1-465.

Hulsey, K. 2015. Cutaway SUV. [Referred 11.10.2015]. Available: http://www.khulsey.com/: http://www.khulsey.com/cutaway-suv-overhead.html.

Jullian. 2015. Blogs.esa.int. [Web document]. Ipdated 27.8.2015. [Referred 11.10.2015]. Available: http://blogs.esa.int/iriss/2015/08/27/driving-three-rovers-Available-space/

Juvinall, R. C. & Marshelk, K. M. 2008. Fundamentals of Machine Component Design 5th Ed. New york: John Wiley and sons, ING. 96 p.

Kattan, P. 2008. MATLAB Guide to Finite Elements an interactive approach 2nd Ed. New York: Springer. 337 p.

GWL power Ltd. 2015. GWL/Power WB-LYP60AHA LiFeYPO4 (3.2V/60Ah) . [Referred 11.25.2015]. Available: http://www.ev-power.eu/_d1575.html

Martins, J. A. & Kövesdy, I. 2012. INTECH [Web database]. [Referred 11.11.2015]. Overview in the Application of FEM in Mining and the Study of Case: Stress Analysis in Pulleys of Stacker-Reclaimers: FEM vs. Analytical Available: http://www.intechopen.com/books/finite-element-analysis-applications-in-mechanical-engineering/overview-in-the-application-of-fem-in-mining-and-the-study-of-case-stress-analysis-in-pulleys-of-sta

Murali, G., Subramanyam, B. & Dulam, N. 2013 Design Improvement of a Truck Chassis based on Thickness. [Web document]. Hyderabad: 2013. [Referred 11.10.2015]. 6 p. Available in PDF-file: http://altairatc.com/india/previousevents/2013/images/presentations/osa_poster_design_improvement_sigmaconsultancy.pdf

Nathan, S. 2014. The Engineer [Web document]. [Referred 11.10.2015]. Available: http://www.theengineer.co.uk/in-depth/the-big-story/innovation-in-the-uk-niche-vehicles-sector/1019080.article

Nikolaos, M. E. 2008. Introduction to EN 1991 [web document]. Brussels: February 2008 [Referred 25.10.2015]. 16 p. Available in PDF-file: http://eurocodes.jrc.ec.europa.eu/doc/WS2008/EN1991_1_Malakatas.pdf

Norton, R. L. 2006. MACHINE DESIGN An Integrated Approach. 3rd Ed. New Jersey: Pearson Education, Inc. Pp. 3-6.

Rajput, R. 2007. A Text book of Manufacturing Technology: Manufacturing Processes. New Delhi: LAXMI PUBLICATION (P) LTD.

Roylance, D. 2001. Finite Element Analysis [web document]. Cambridge: February 2001 [Referred 11.11.2015]. Massachusetts Institute of Technology. 16 p. Available in PDF-file: http://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/fea.pdf

Siegwart, R. & Nourbakhsh, R. I. 2004. Introduction to Autonomous Mobile Robots. London: The MIT press. Pp. 41-45.

Solidworks. 2015. [Dassault system webpage]. [Referred 10.11.2015]. Available: http://www.solidworks.com/sw/why-solidworks/solidworks-productivity.htm

Spider. 2013. How to read an outrigger counterweight chart or fulcrum point load chart [web document]. [Referred 11.15.2015]. Pp. 109-113. Available in PDF-file: http://www.spiderstaging.com/PDF%20Files/Catalog/Temporary%20Access%20-%20Rigging%20Products%20-%20Counterweight%20Fulcrum%20Load%20Charts.pdf

Steven, B. 2009. Design and development of a novel Omni-directional platform [Web document]. Ontario: August 2009. [Referred 11.9.2015]. University of Ontario Institute of technology. 132 p. +appendixes 61 p. Available in Pdf –file: http://www.collectionscanada.gc.ca/obj/thesescanada/vol1/OOSHDU/TC-OOSHDU-29.pdf

Strauss, P. 2013. 95octane [Web document]. Updated 18.5.2014. [Referred 11.10.2015]. Available: http://95octane.com/2014/05/18/jaguar-xe-sport-sedan-teased/

Tebby, S., Esmailzadeh, E. & Barari, A. 2011. Methods to Determine Torsion Stiffness in an Automotive Chassis [Web document]. Canada: 2011. [Referred 30.11.2015]. Computer aided design and application. Pp. 67-75. Available in pdf-file: http://www.cadanda.com/CAD_PACE_1__67-75.pdf

The free dictionary by farlex 2010.The free dictionary by farlex. [Referred 11.15.2015], Available: http://encyclopedia2.thefreedictionary.com/Dynamic+Factor+of+a+Motor+Vehicle

Trobaugh, J. 2011. Winning design LEGO MINDSTORMS NXT design patterns for fun and competiton. New York: Apress. Pp. 25-26.

Vehicle Safety Research Integration Symposium. 1973. Research Institute's Office of Operating Systems Research, Office of Vehicle Structures. Washington, D.C. 10 p.

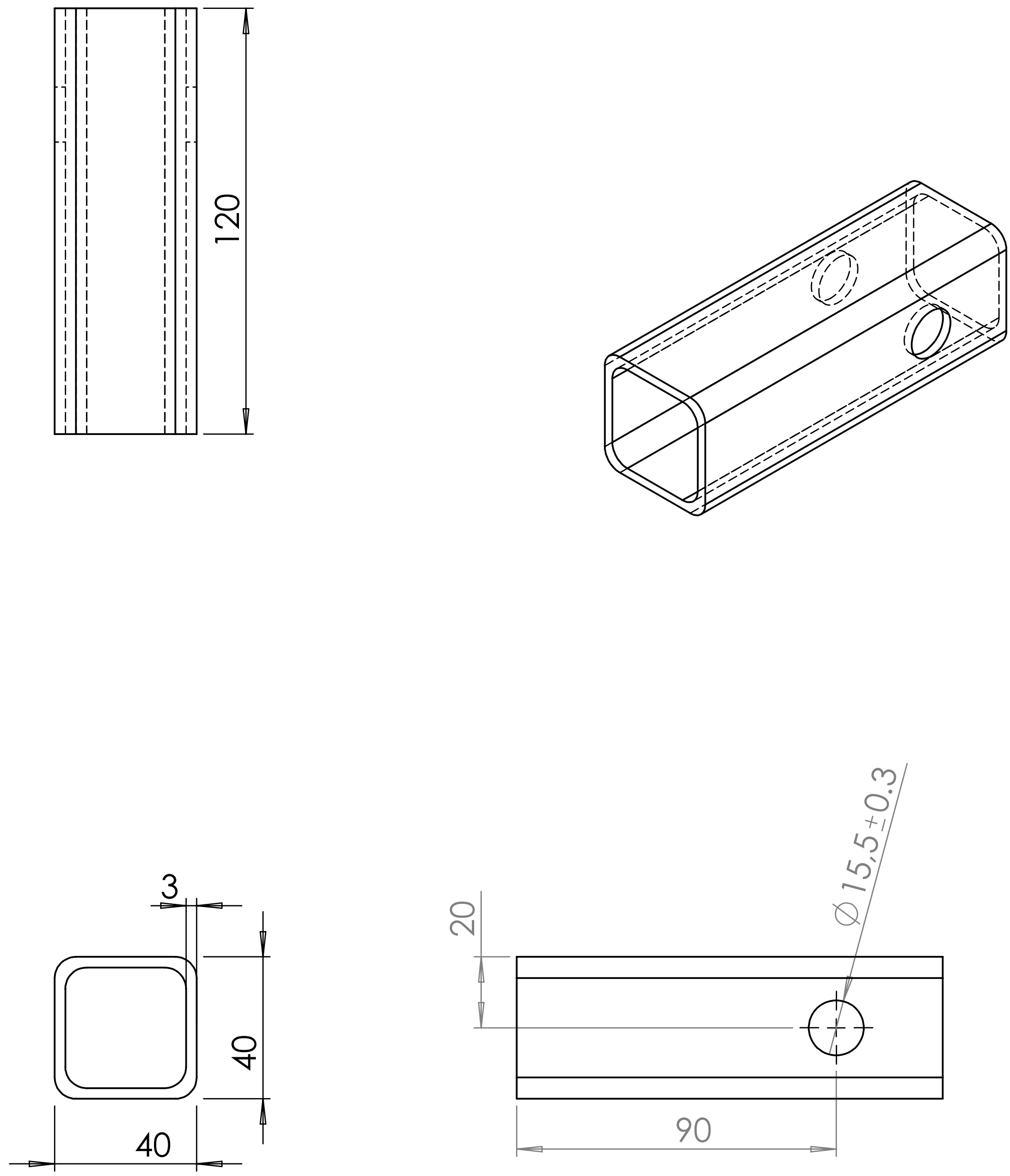
Wijckmans, F. & Tuytschaever, F. 2011. Vertical agreements in competition law 2nd ed. Oxford: Oxford university press. 320 p.

Xie, X. 2015. Design for Manufacture and Assembly [Web document]. Utah [Referred 128.10.2015]. Dept. of Mechanical Engineering, University of Utah. 12 p. Available in PDF-file: http://home.utah.edu/~u0324774/pdf/DFMA.pdf

Yong, W. G. & Budynas, G. R. 2011 Roark's Formulas for stress and strain. 8th Ed. New York: McGraw-Hill. 190 p.

Appendix I

Engineering Drawings



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DEBURR AND BREAK SHARP EDGES

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CHK'D			
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Q.A			

TITLE: 200mm40by40beam

MATERIAL:
S235JRH (rukki square)

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A4

WEIGHT:

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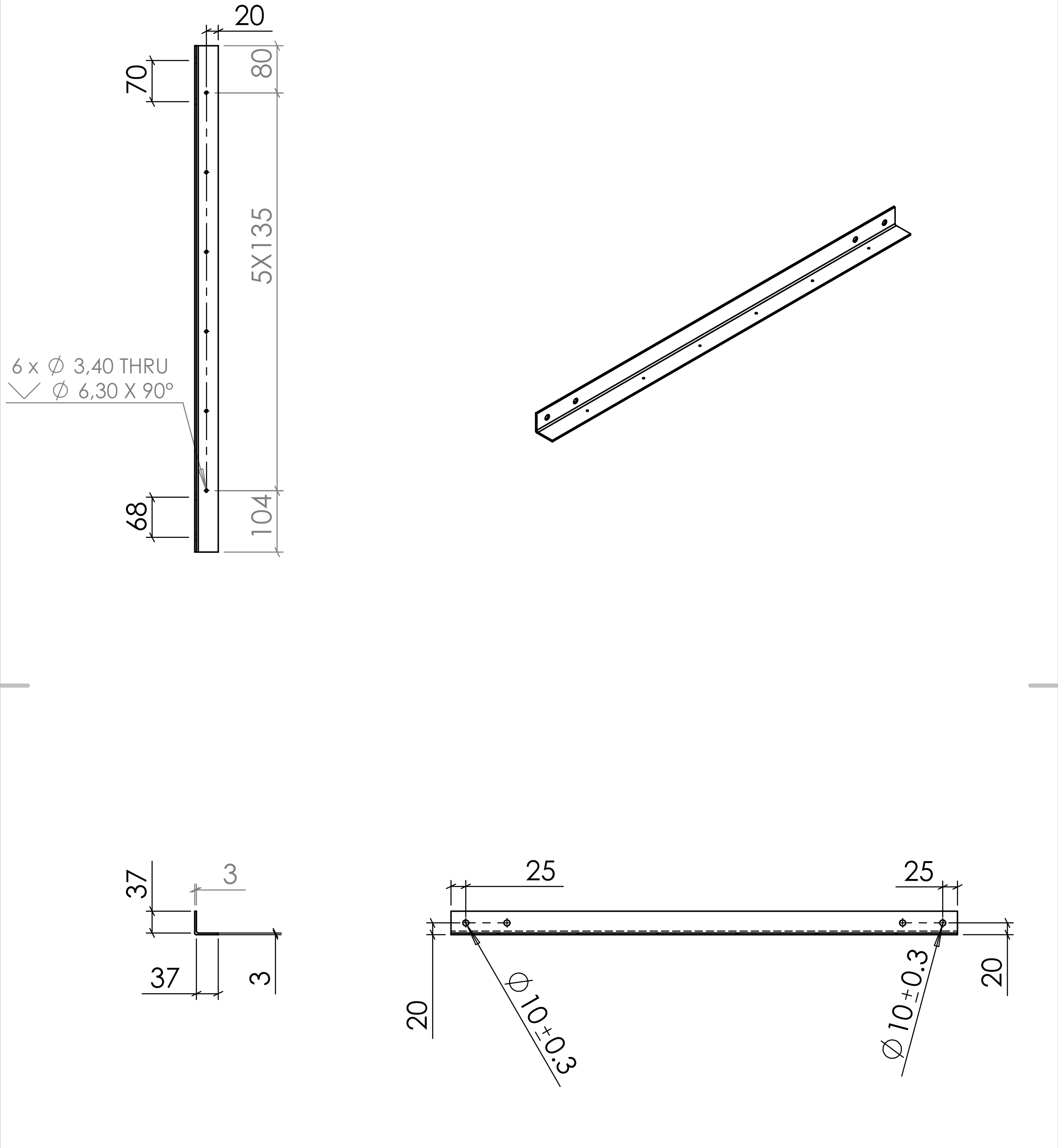
SHEET 1 OF 1



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TITLE:

489anglebeam

MATERIAL:Rukkiś cold formed equal angle

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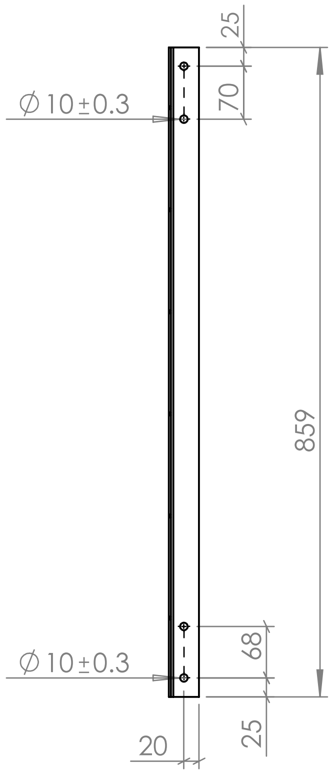

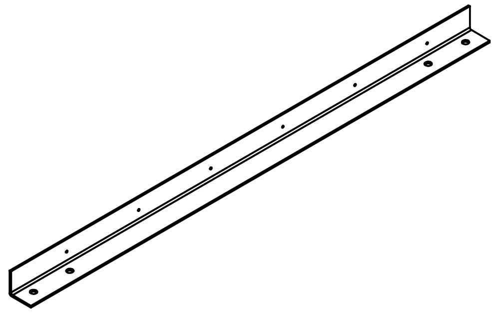

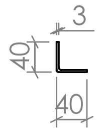

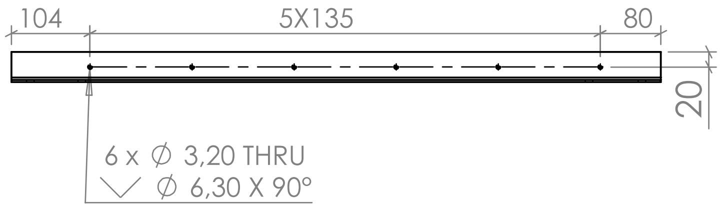

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TITLE: 489anglebeamright

MATERIAL: Ruukis cold formed eqal angle

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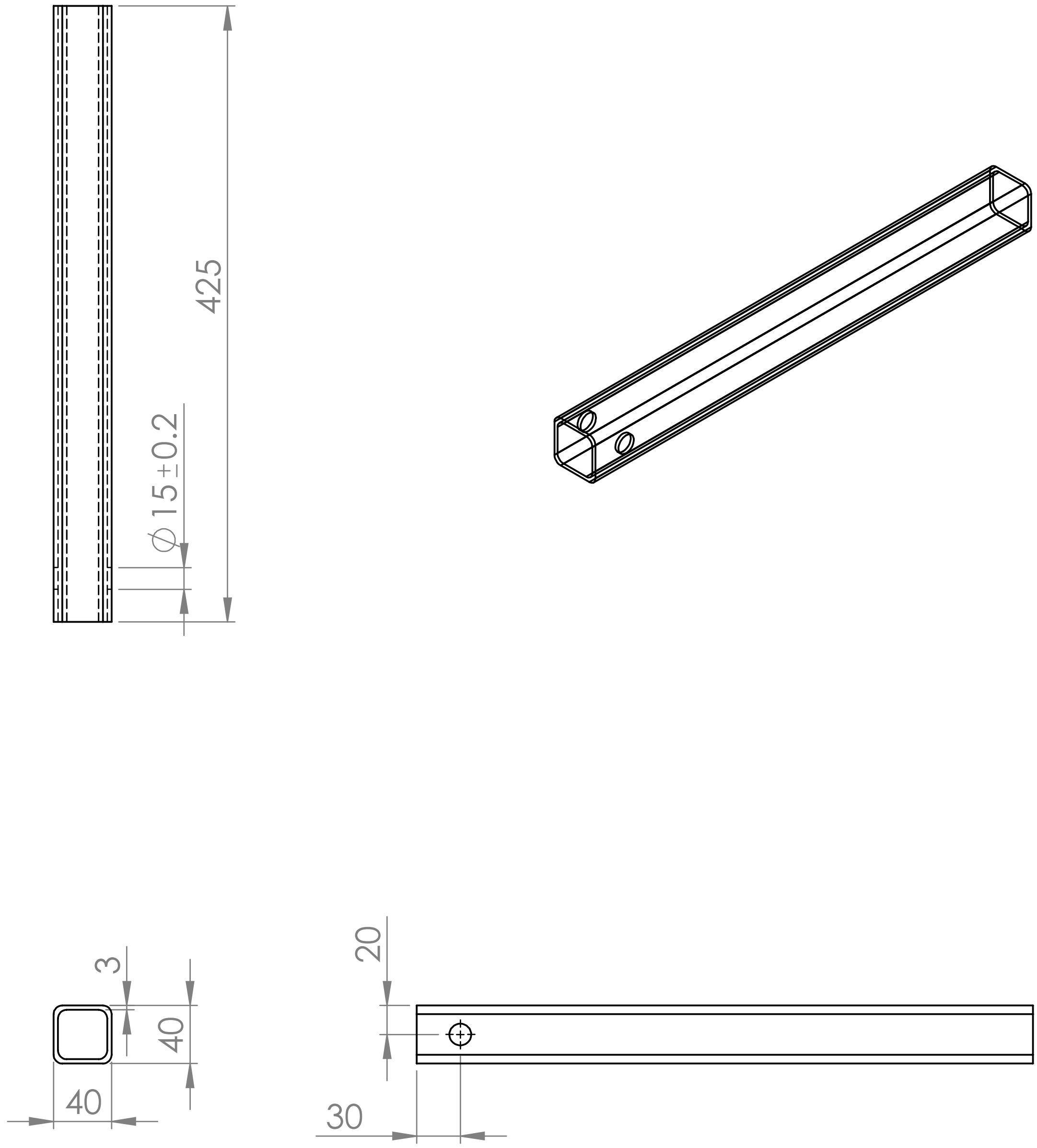

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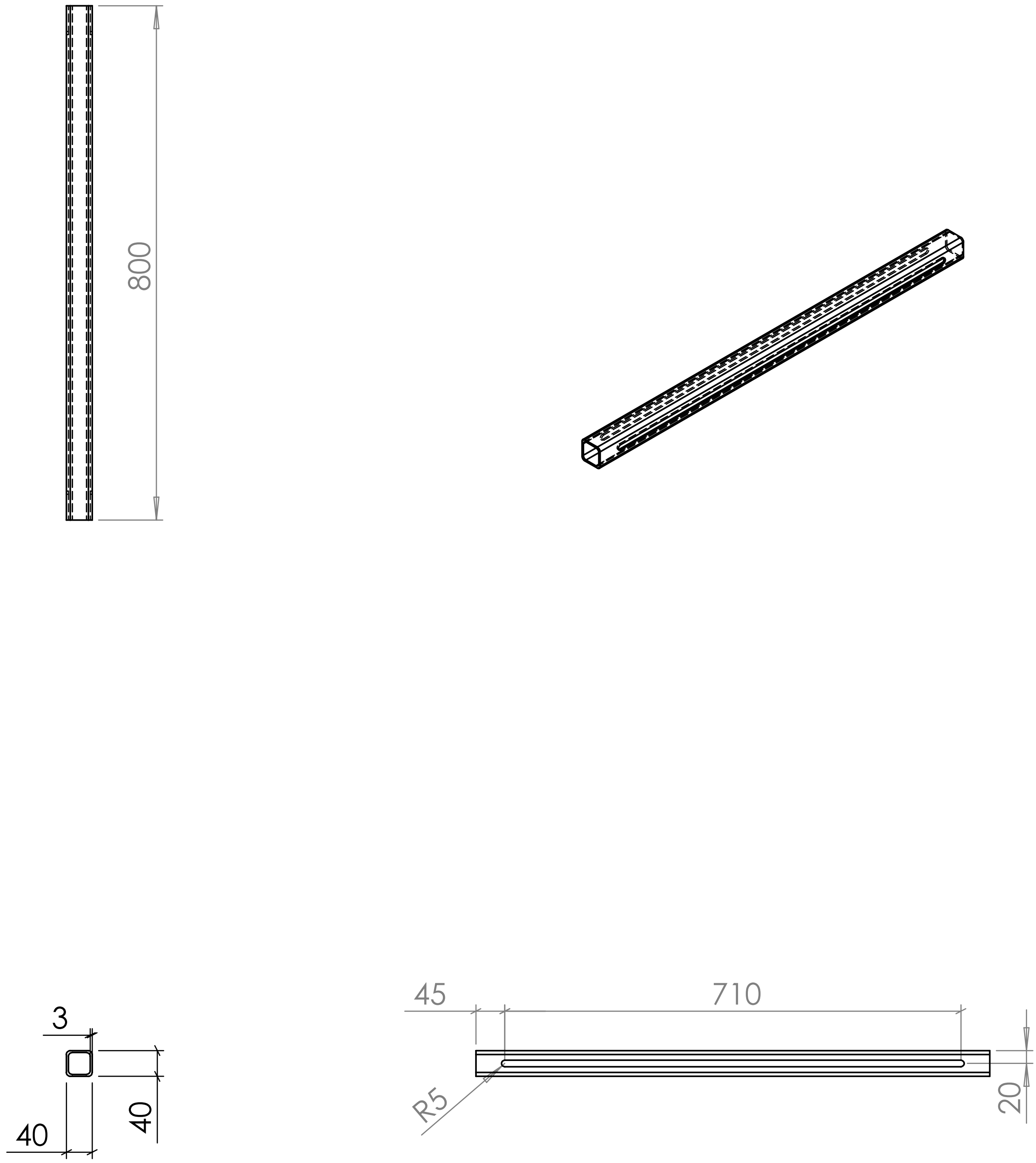

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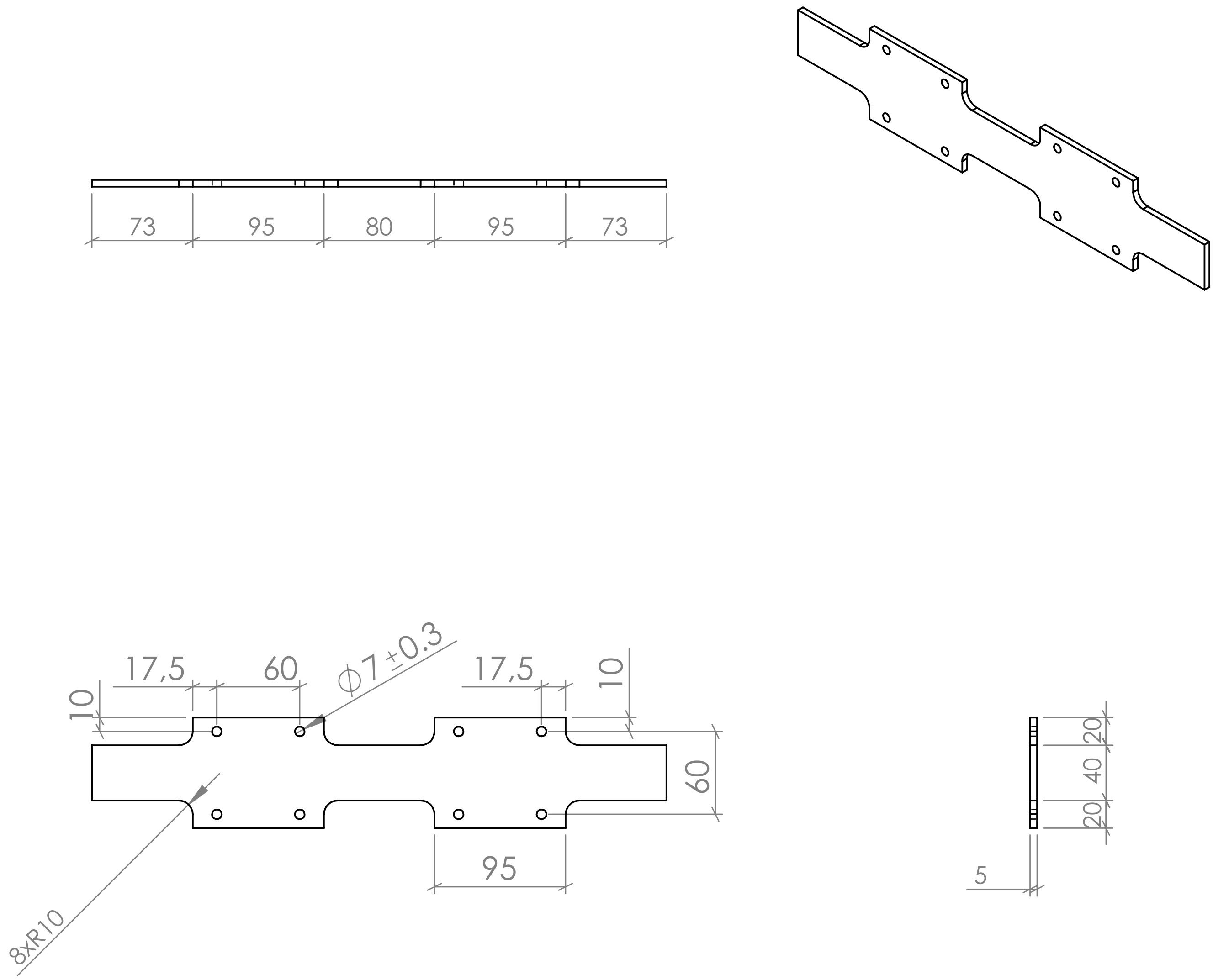

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MATERIAL: OPTIM QM STRUCTURAL STEEL

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TITLE:

beveralgear

DWG NO. 7

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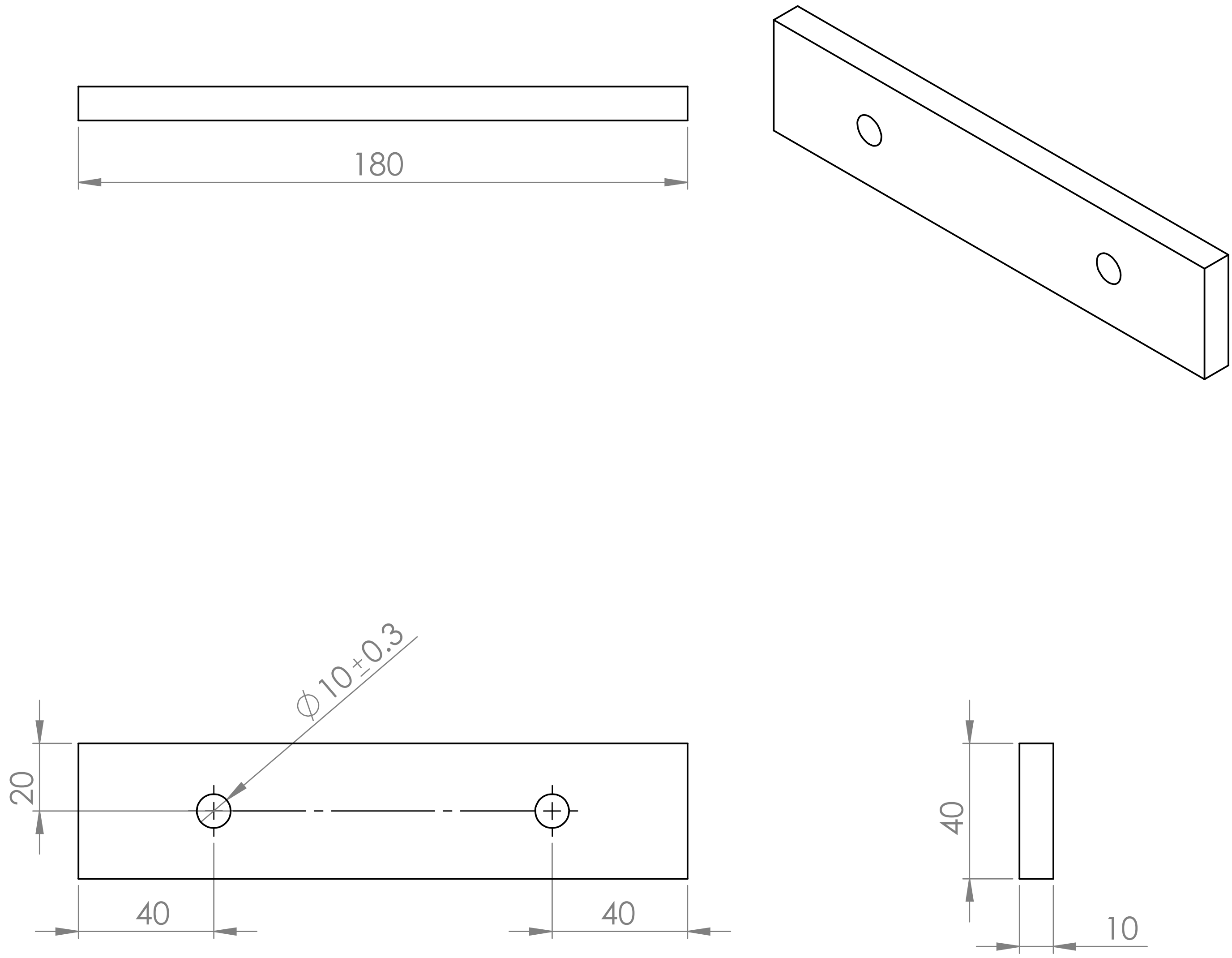

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MATERIAL:optim QC 900 structural steel (ruukki)

WEIGHT:

TITLE:

extensionplatebeamfor controller

DWG NO 8.

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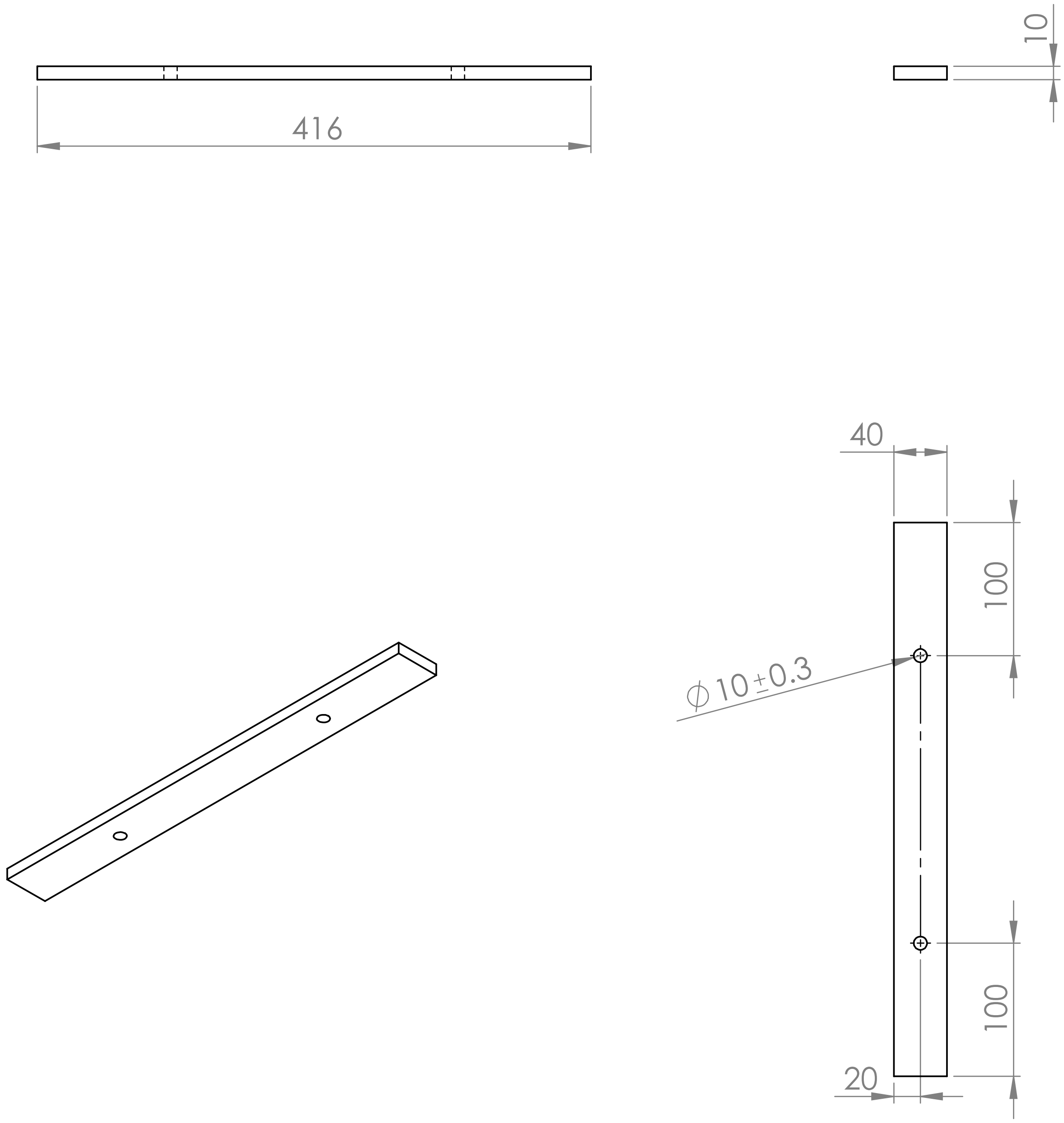
SHEET 1 OF 1



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APPV'D					
MFG					
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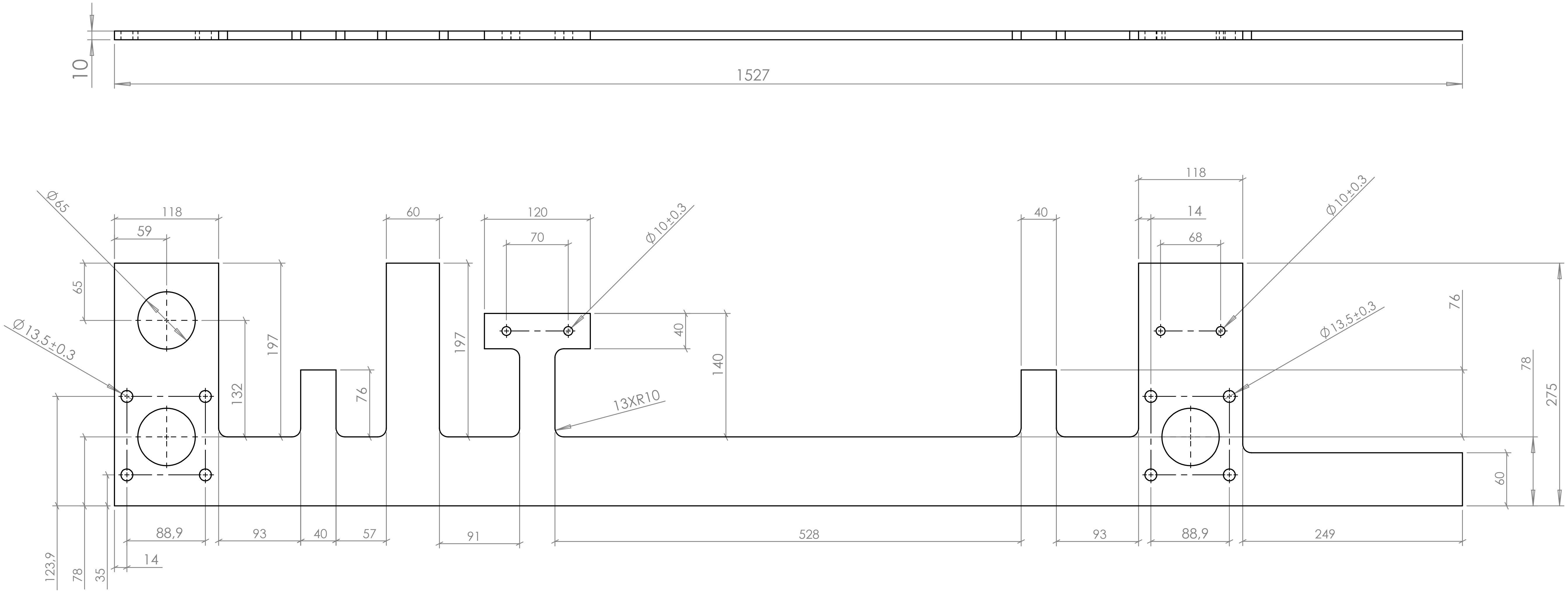

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CHK'D					
APPV'D					
MFG					
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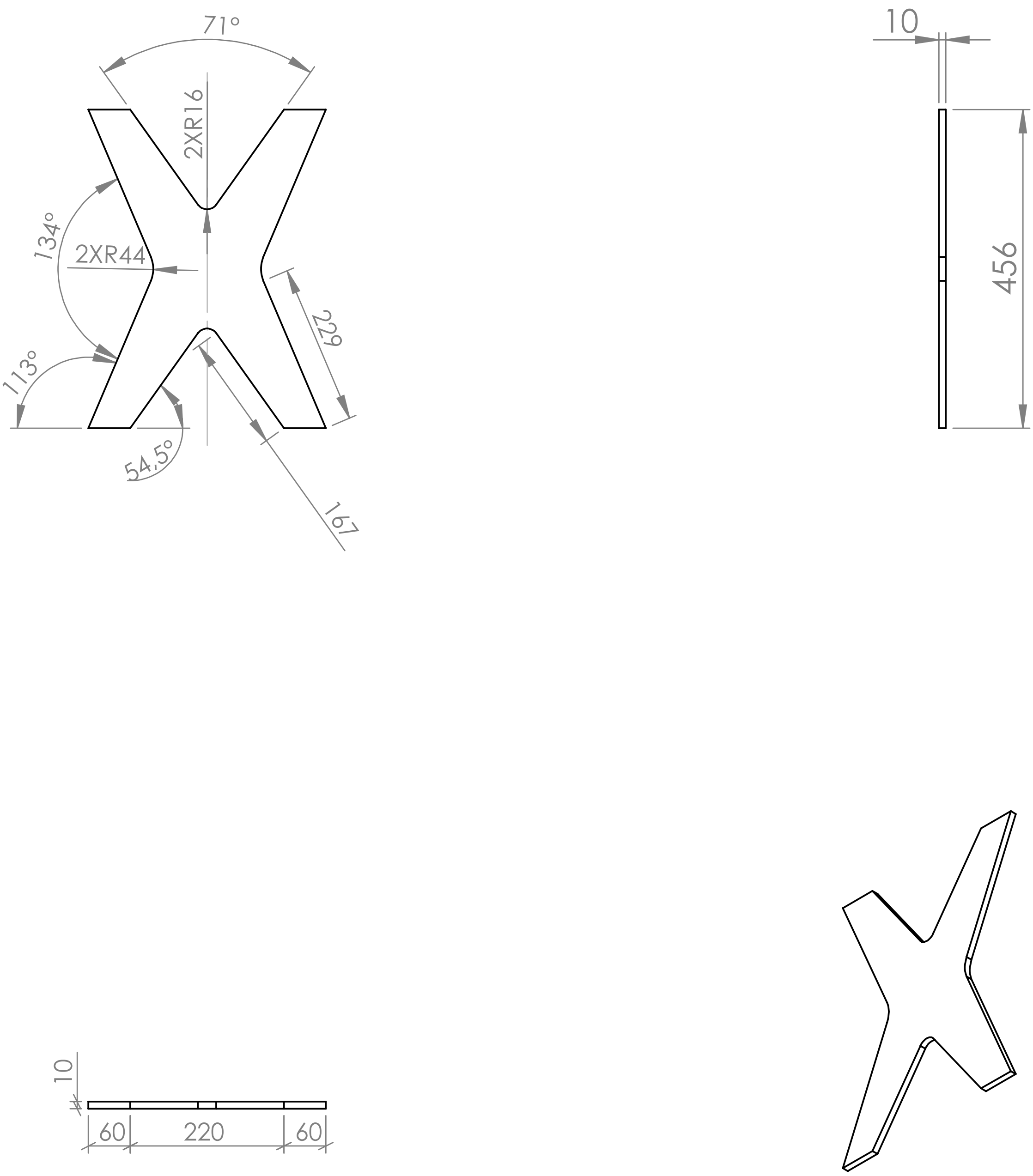
SolidWorks Educational Edition.
For Instructional Use Only.



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APPV'D					
MFG					
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MATERIAL: Optim 900 QC (rukki)

WEIGHT:

TITLE:

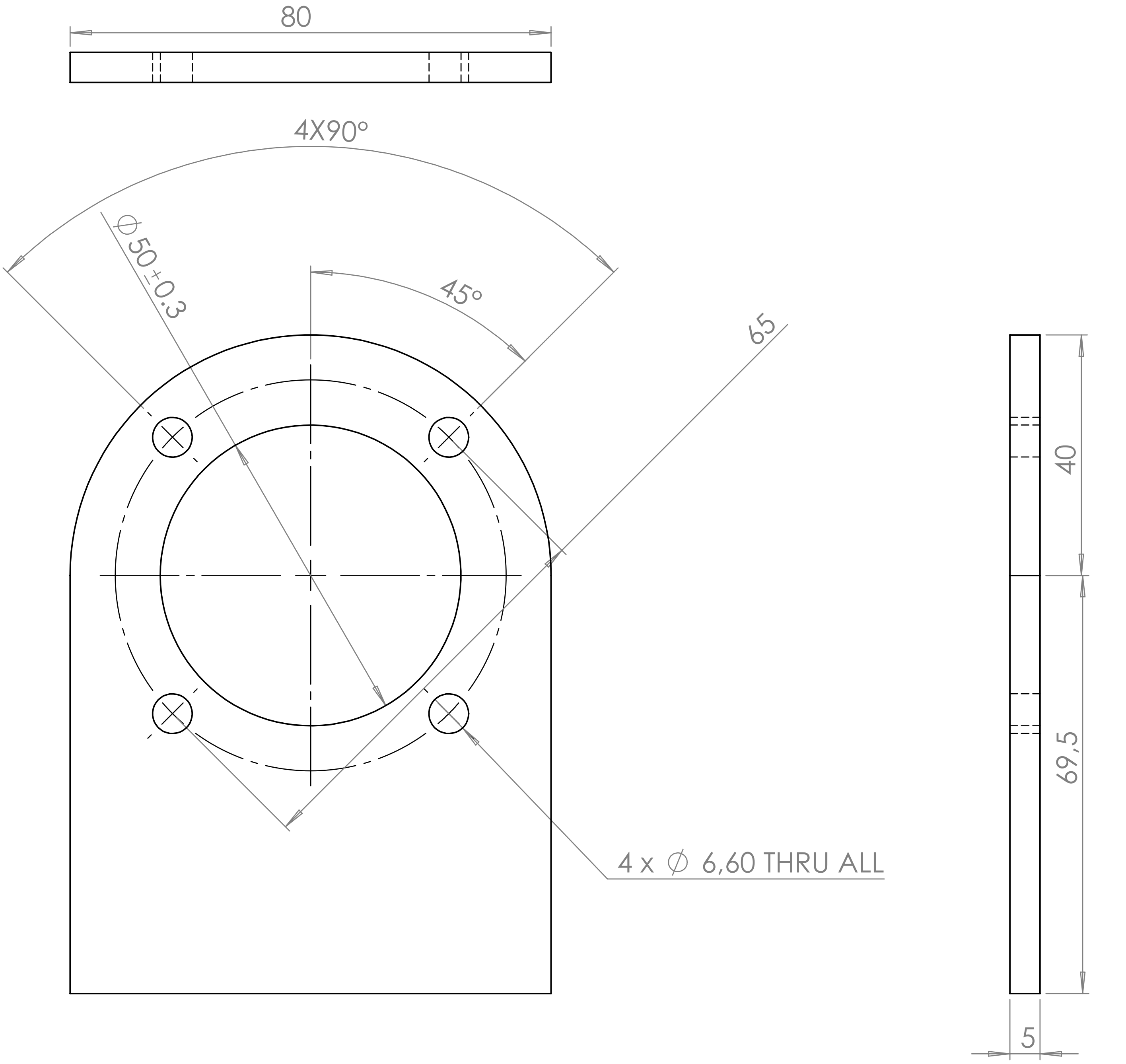
tjoint support

DWG NO. 11

A4

SCALE:1:10

SHEET 1 OF 1



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MATERIAL:
[illegible] STRUCTURALSTEELS

WEIGHT:

TITLE:

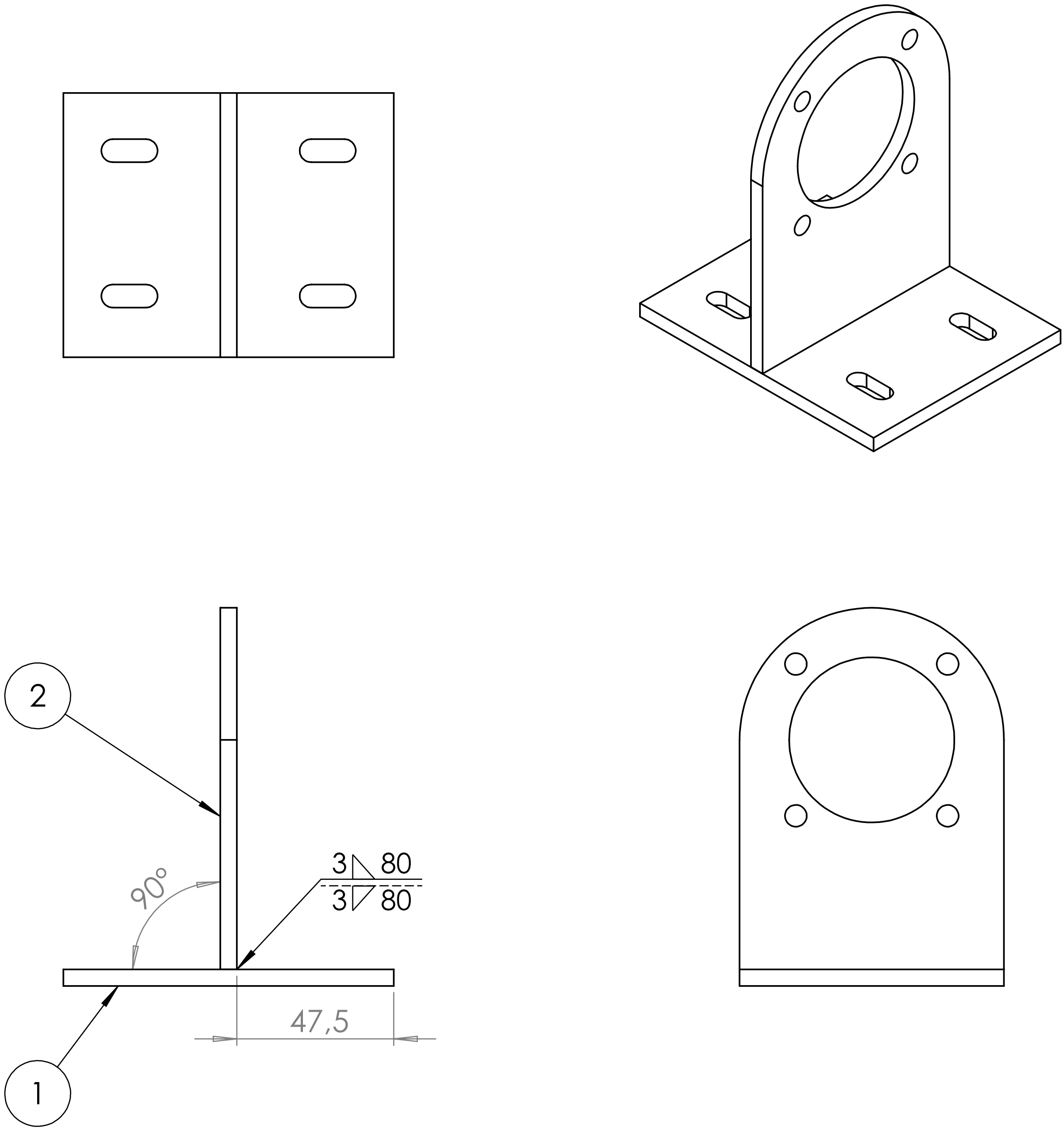
motormounting newgenerationX1

DWG NO. 12

A4

SCALE:1:1

SHEET 1 OF 1



2	motormounting new generationX1
1	newmotormountingplate with slot1

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MATERIAL:

WEIGHT:

TITLE:

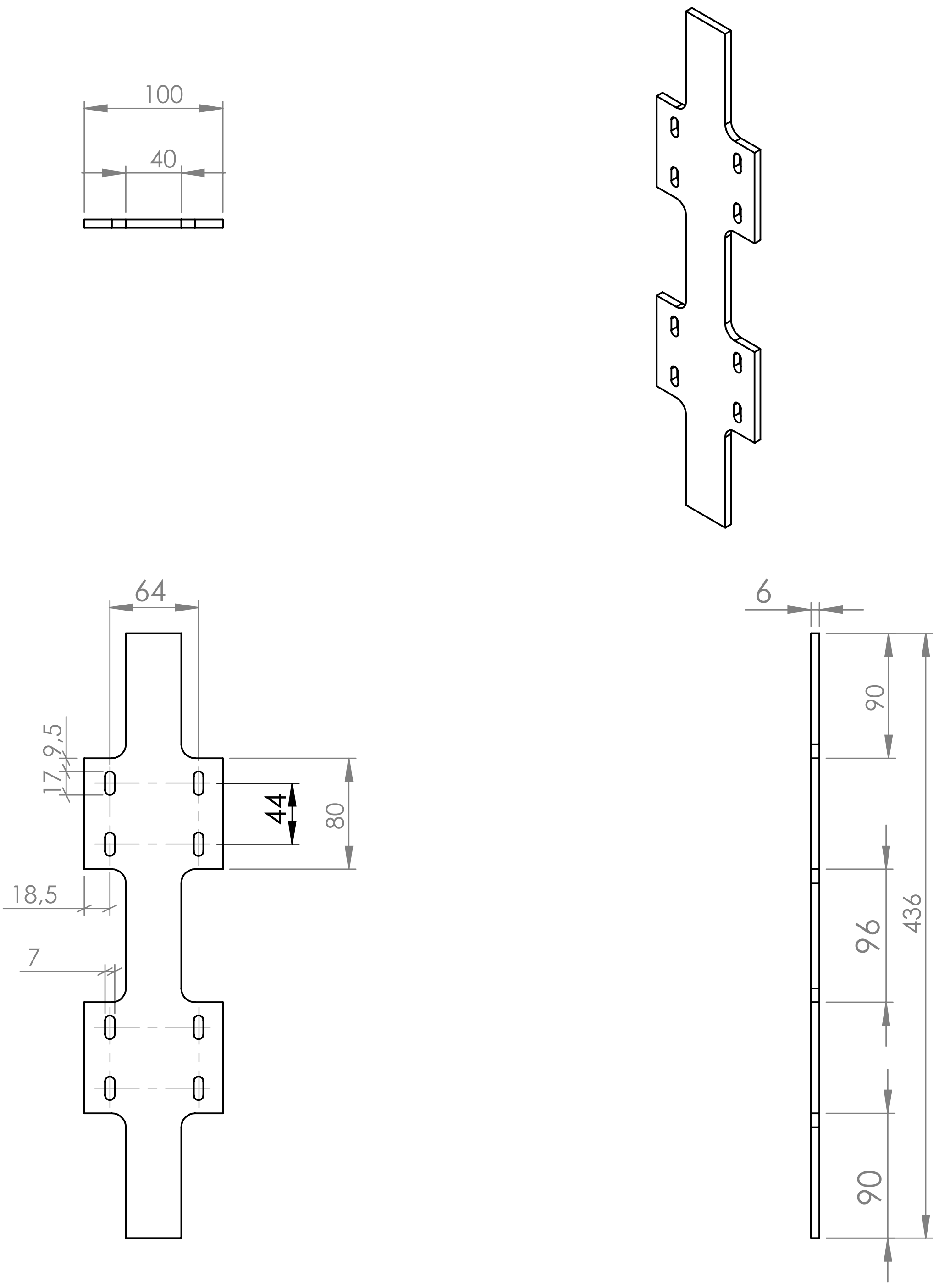
motormountingassembly

DWG NO. 15

A4

SCALE:1:2

SHEET 1 OF 1



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DEBUR AND BREAK SHARP EDGES

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	NAME	SIGNATURE	DATE
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APPV'D			
MFG			
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MATERIAL: OPTIMAL QC 900
STRUCTURAL STEEL

WEIGHT:

TITLE:

motormountingplatebeam

DWG NO. 13

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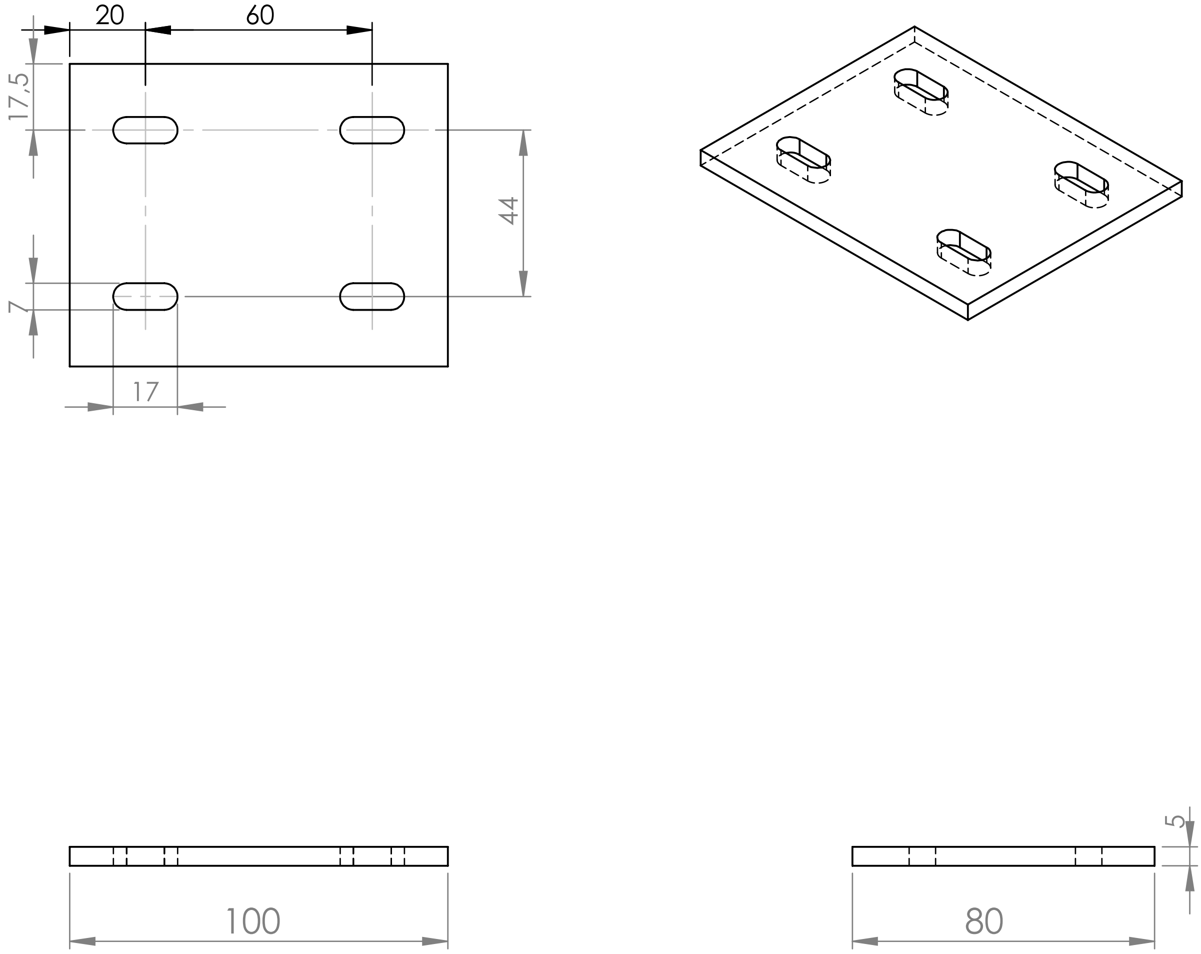
SHEET 1 OF 1



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APPV'D			
MFG			
Q.A			

MATERIAL: OPTIM QC STRUCTURAL STEEL

WEIGHT:

TITLE:

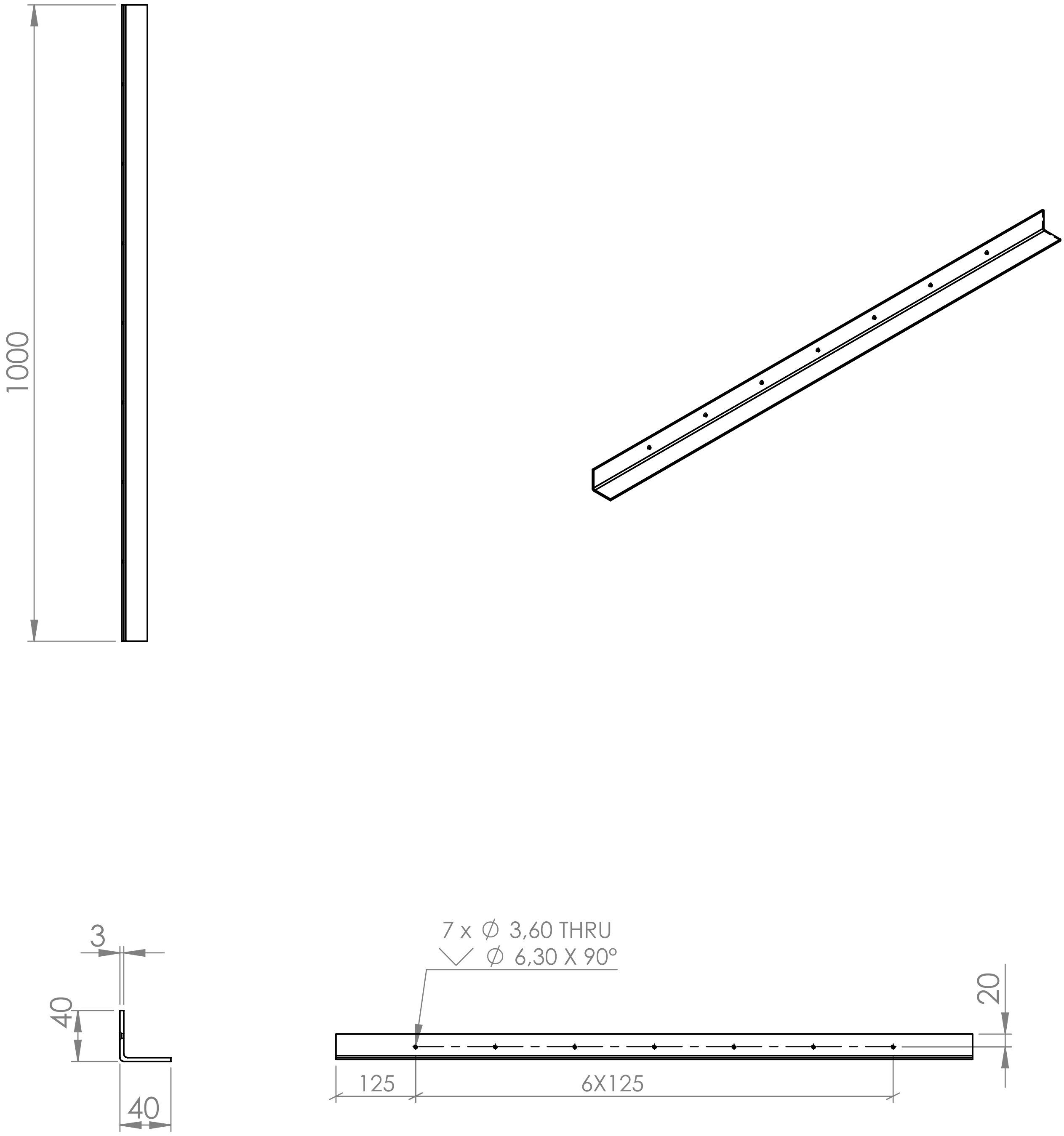
newmotormountingplatewith slots1

DWG NO. 14

A4

SCALE:1:2

SHEET 1 OF 1



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

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

1manglebeam

MATERIAL: Ruukki's cold-formed steel (equal angle)

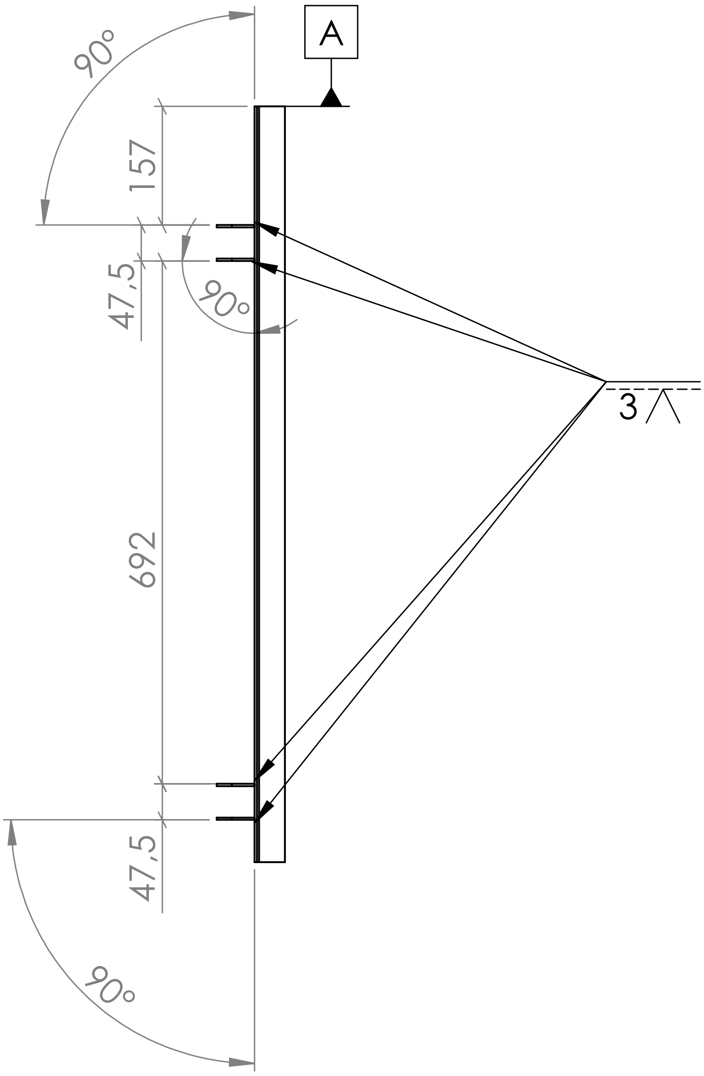
DWG NO. 16

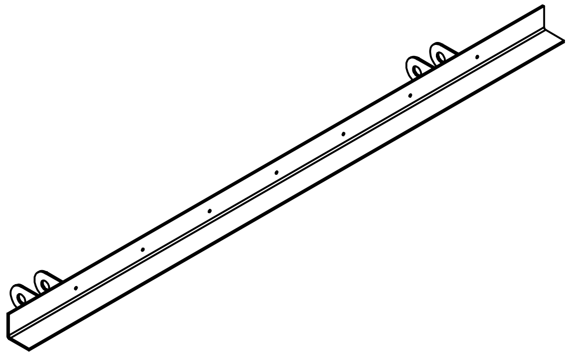
A4

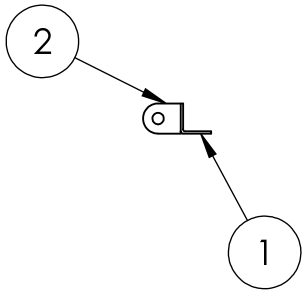
WEIGHT:

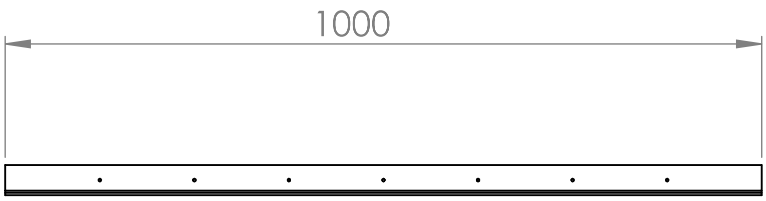
SCALE:1:10

SHEET 1 OF 1



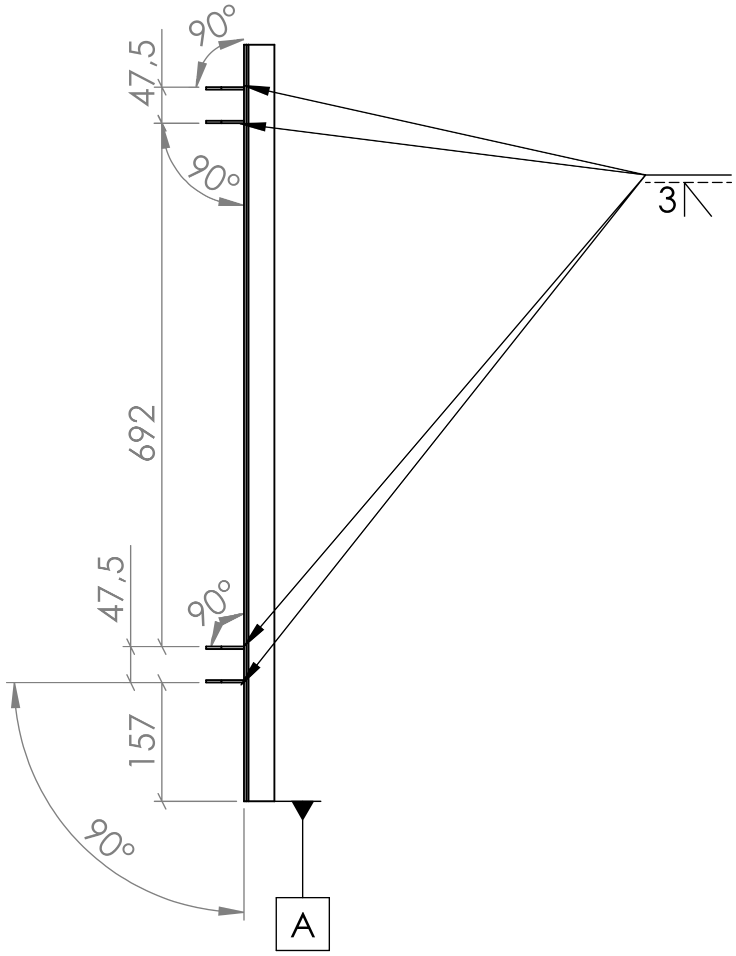


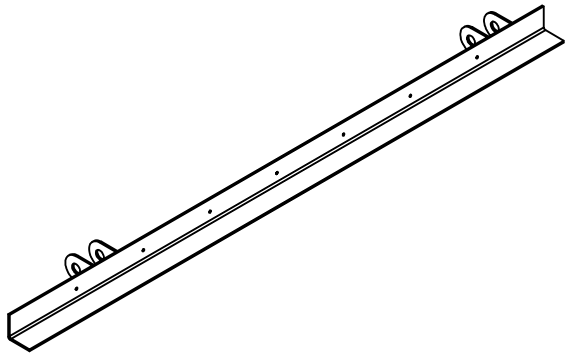


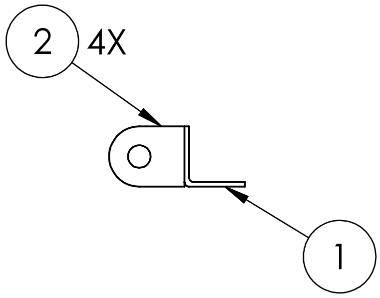


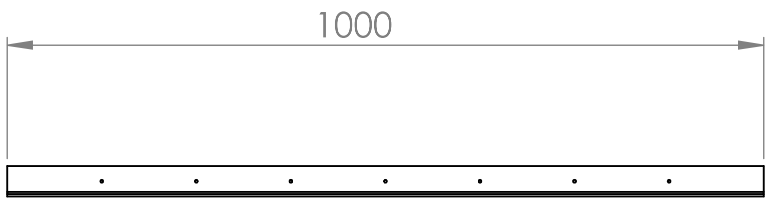
2	quadcopter support connector
1	1m angle beam

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN					quadcopterleftsupport	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. 18	A4
				WEIGHT:	SCALE:1:10	SHEET 1 OF 1









2	quadcopter support connctor
1	1m angle beam

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: quadcopterrightsupport

MATERIAL:

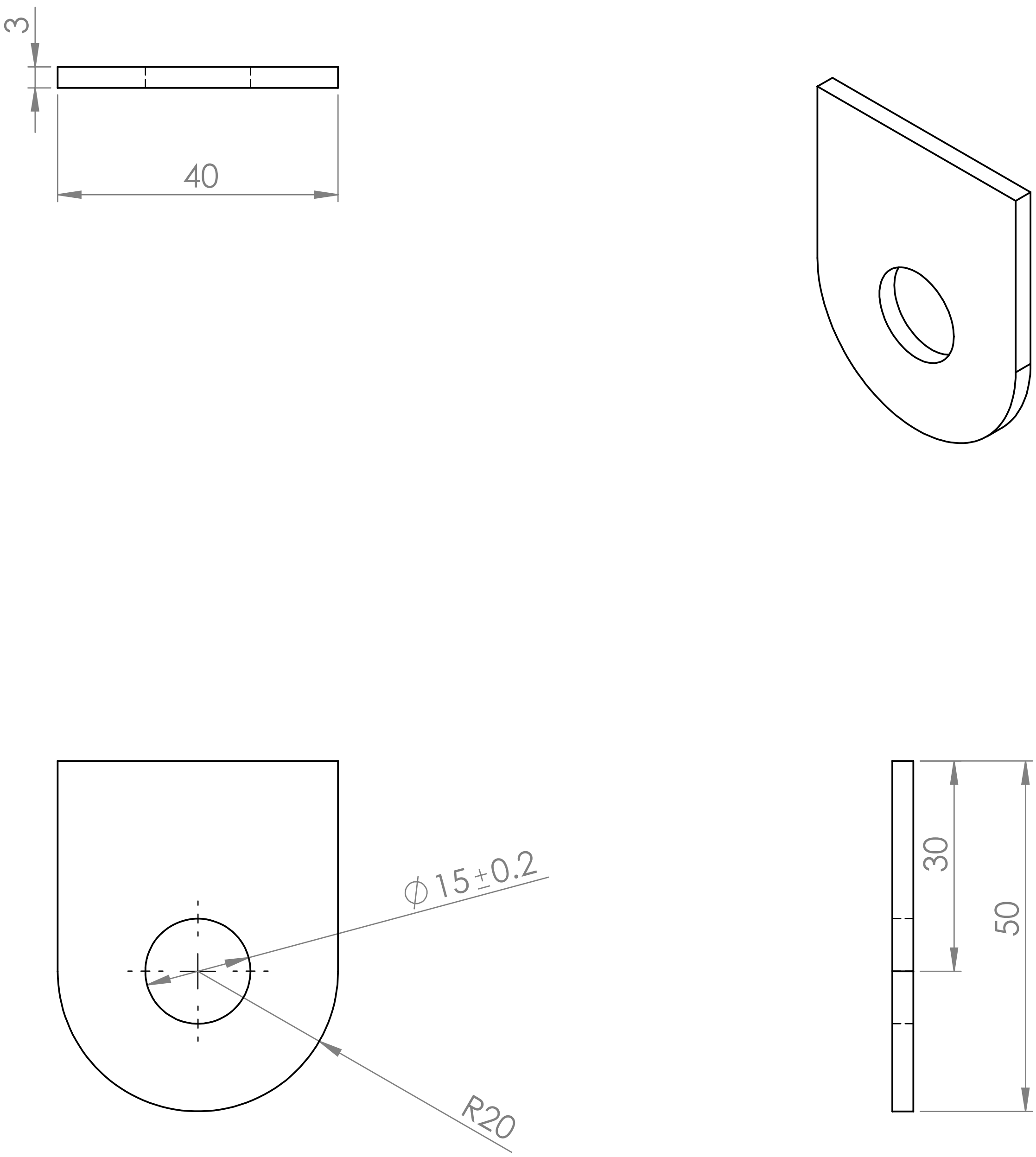
DWG NO. 19

A4

WEIGHT:

SCALE:1:10

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

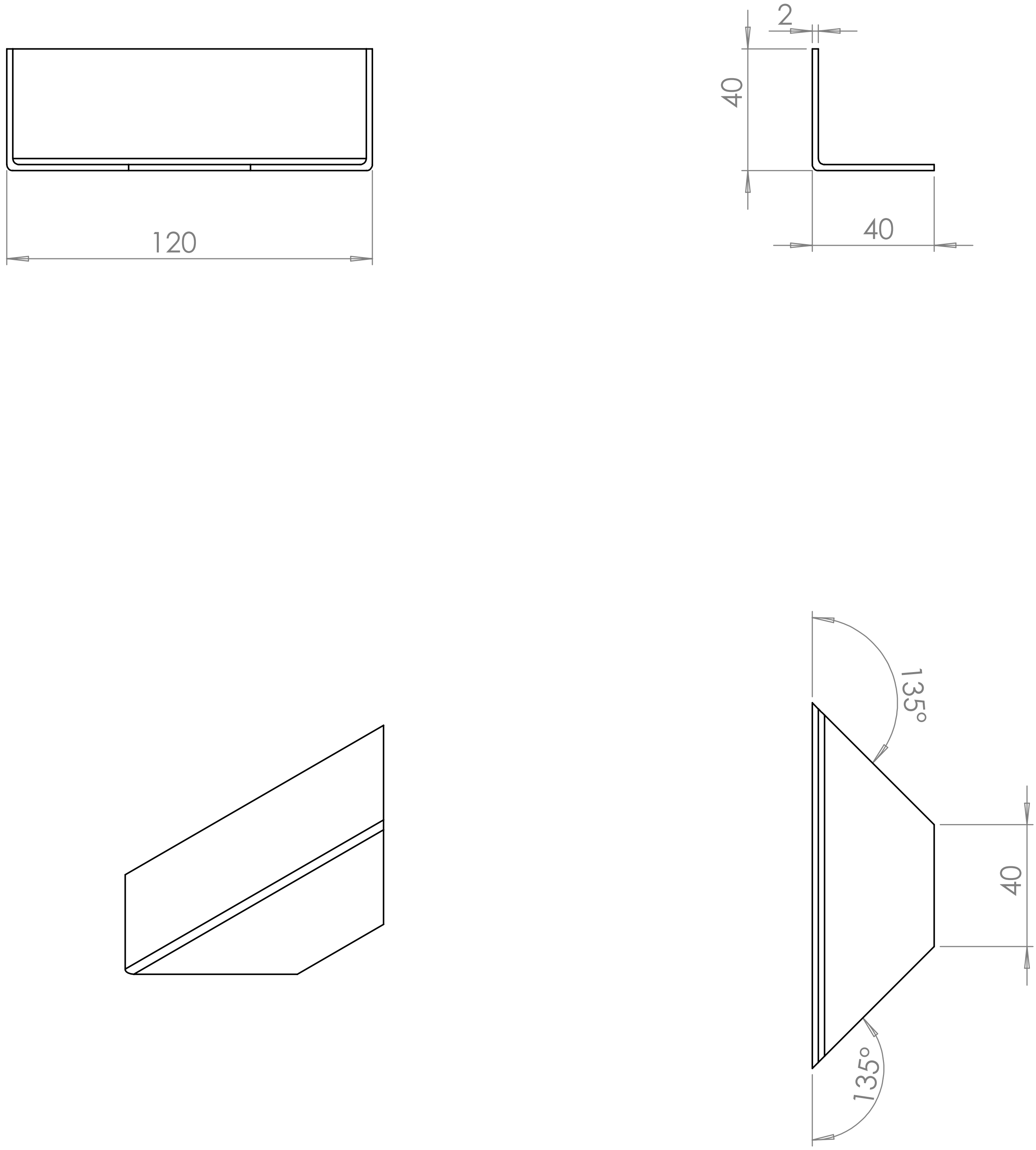
quadcoptersupportconnector

DWG NO.17

A4

SCALE:2:1

SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

140mm angle plate

MATERIAL: Ruukki's cold-formed steel (equal angle)

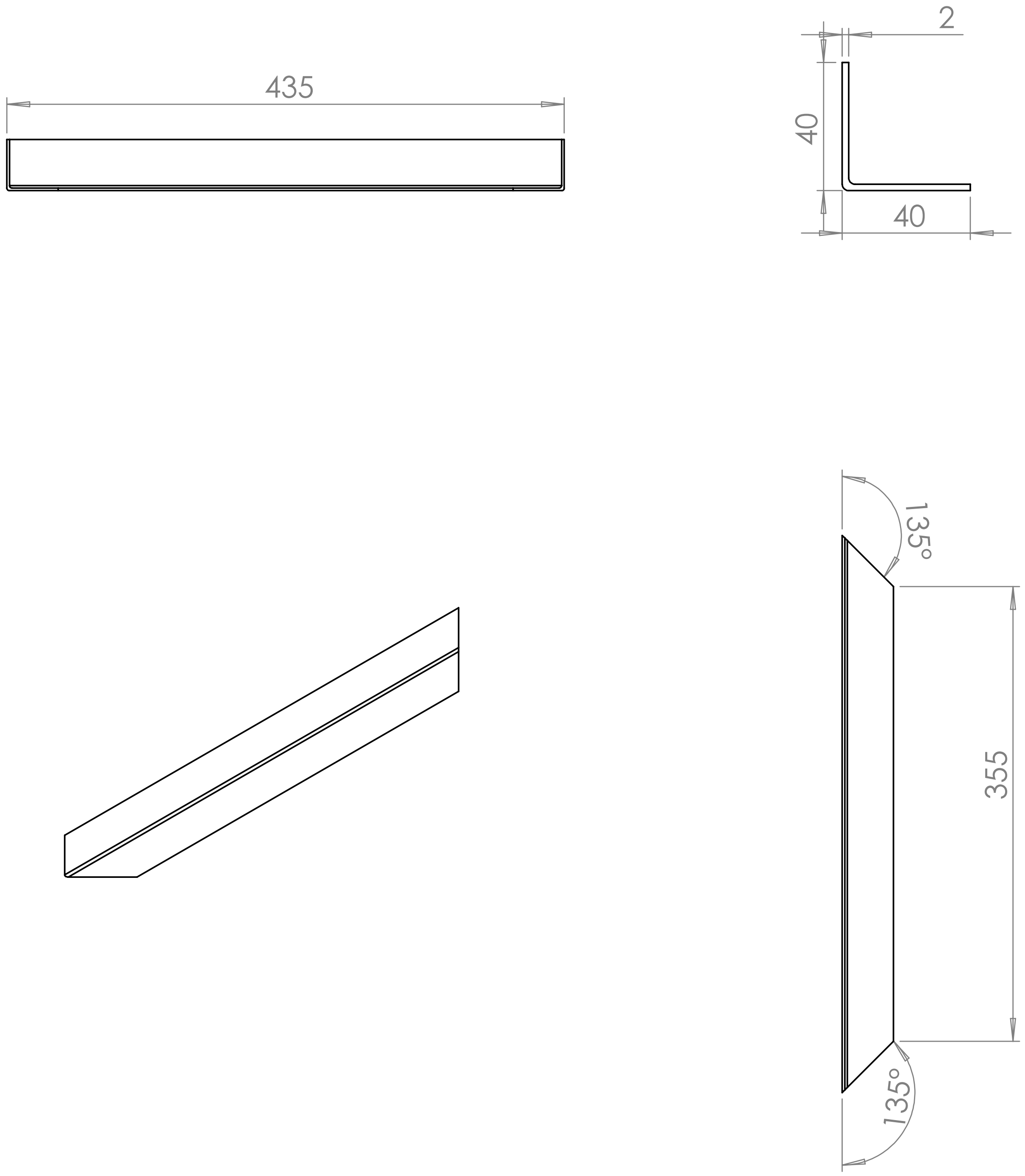
DWG NO. 21

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL: Ruukki’s cold-formed steel (equal angle)

WEIGHT:

TITLE:

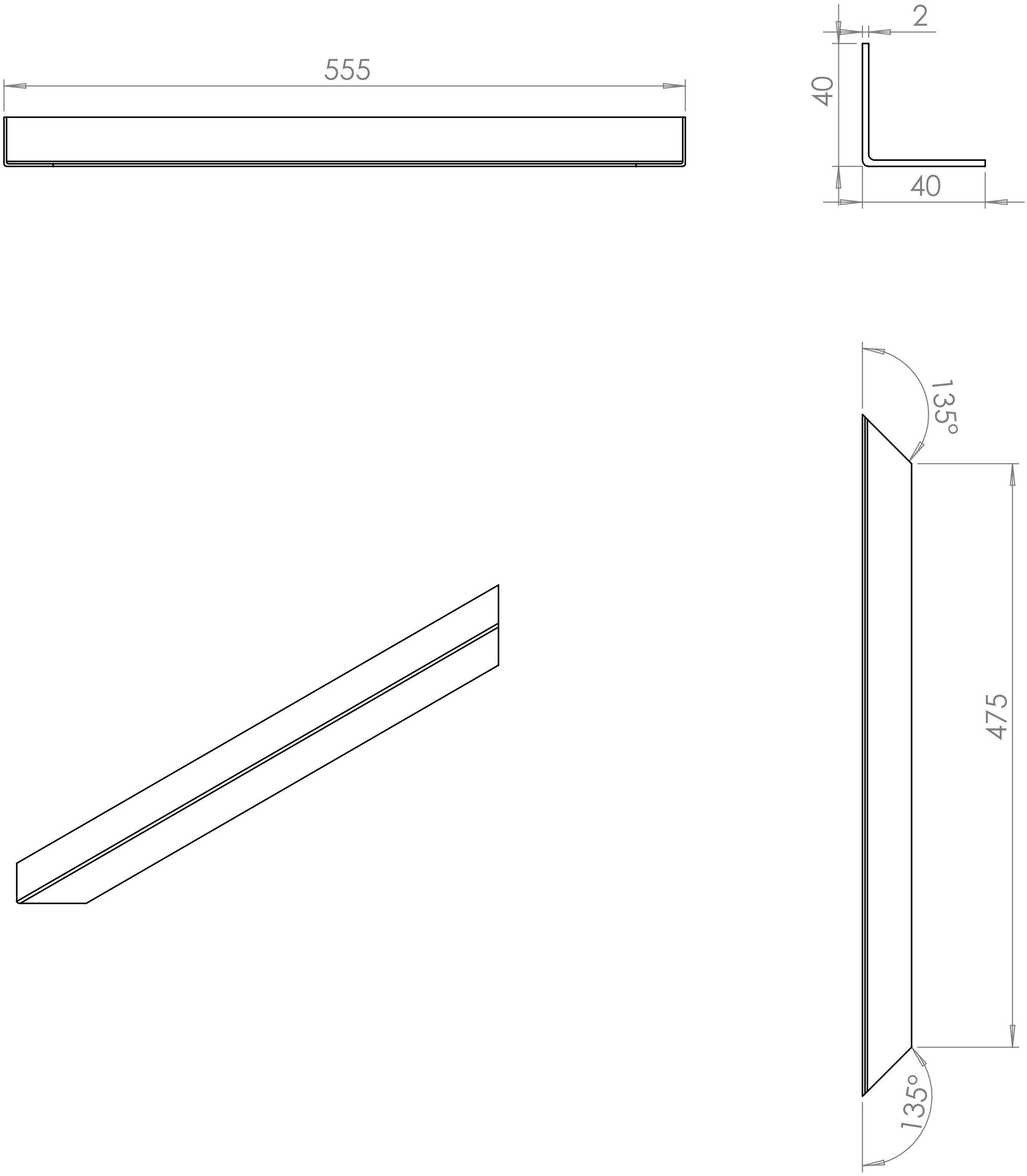
435mmmm angle plate

DWG NO. 22

A4

SCALE:1:1

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

552mmmm angle plate

MATERIAL: Ruukki's cold- formed steel (equal angle)

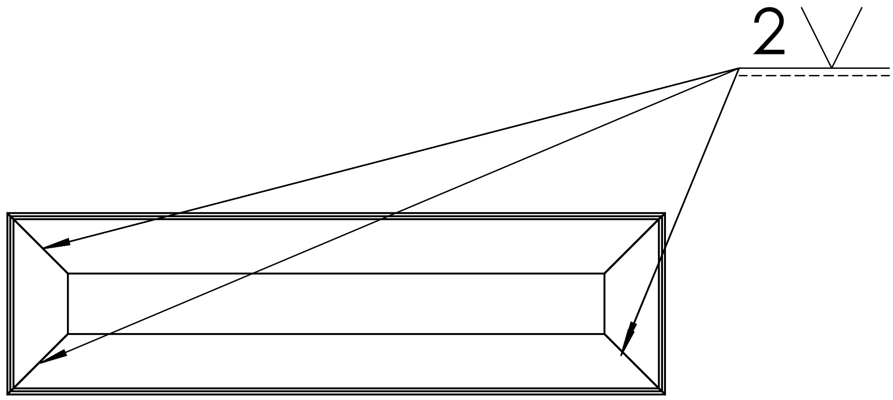
DWG NO.23

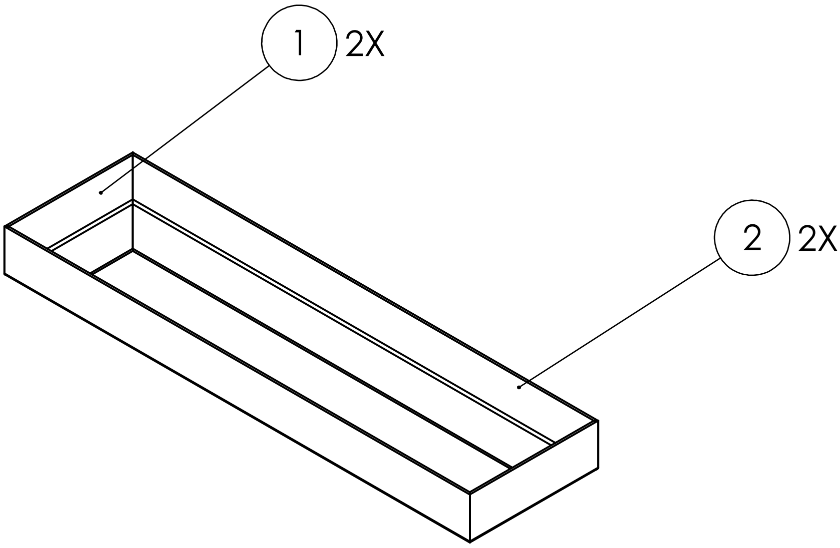
A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1





1	140mm angle plate
2	435mmangle plate

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL:

WEIGHT:

TITLE:

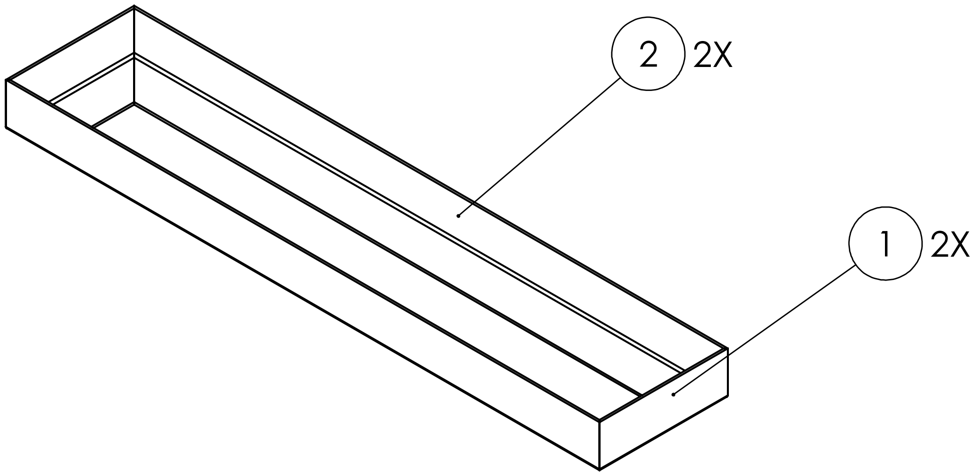
7battrybox

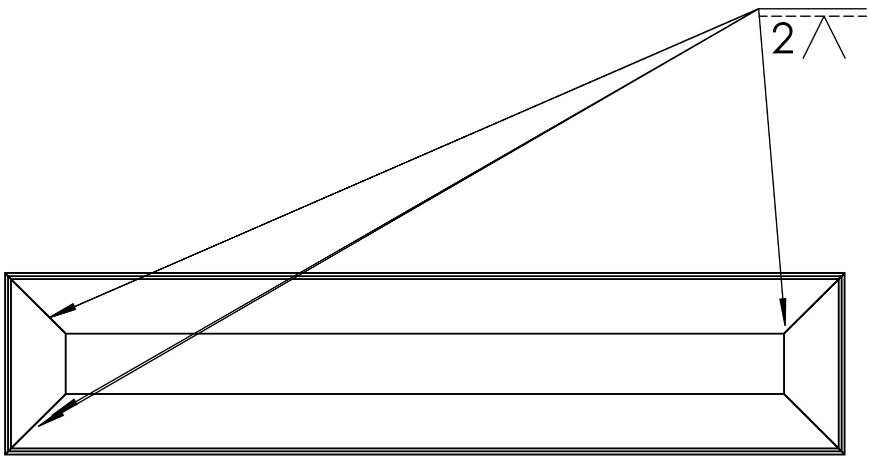
DWG NO.24

A4

SCALE:1:5

SHEET 1 OF 1





1	140mmangle plate
2	552 angle plate

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

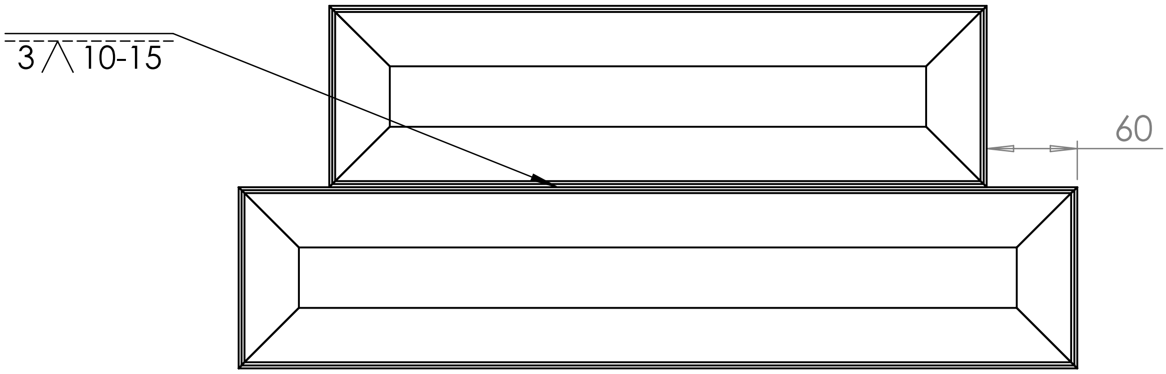
9battrybox

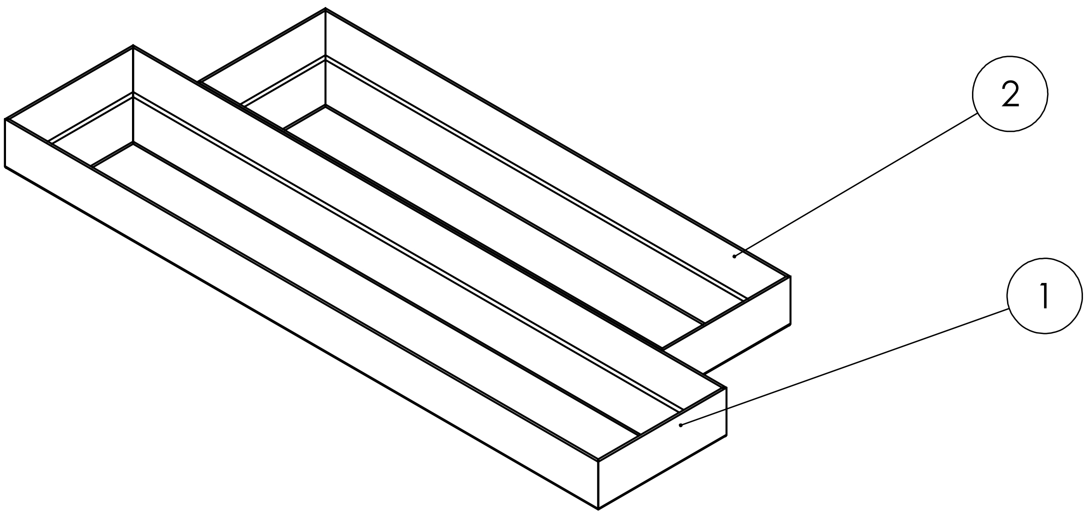
DWG NO.25

A4

SCALE:1:1

SHEET 1 OF 1





2	7 battry box
1	9 battrybox

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

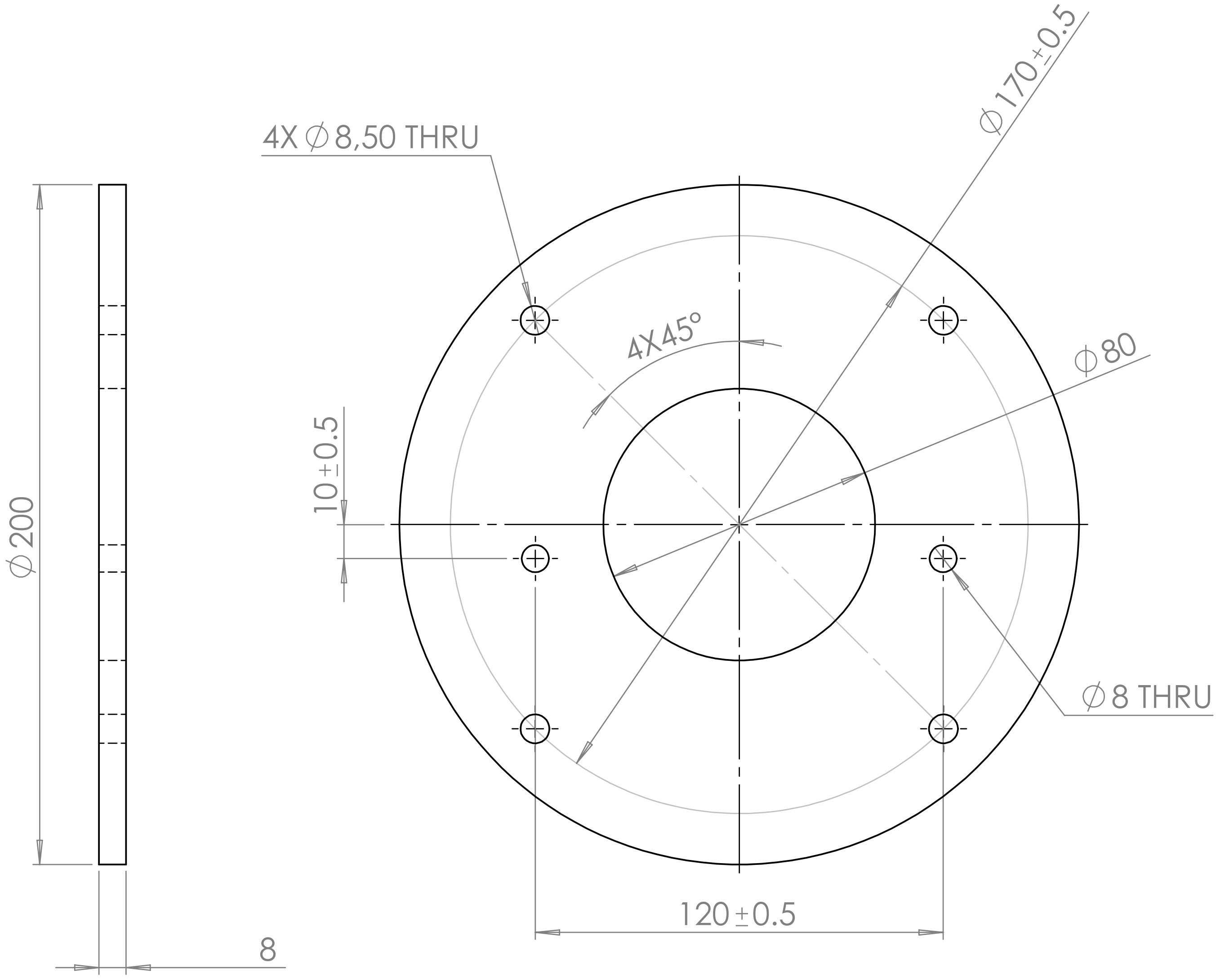
completbattrybox

DWG NO.26

A4

SCALE:1:5

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

MATERIAL: Optim 900 QC (rukki)

WEIGHT:

TITLE:

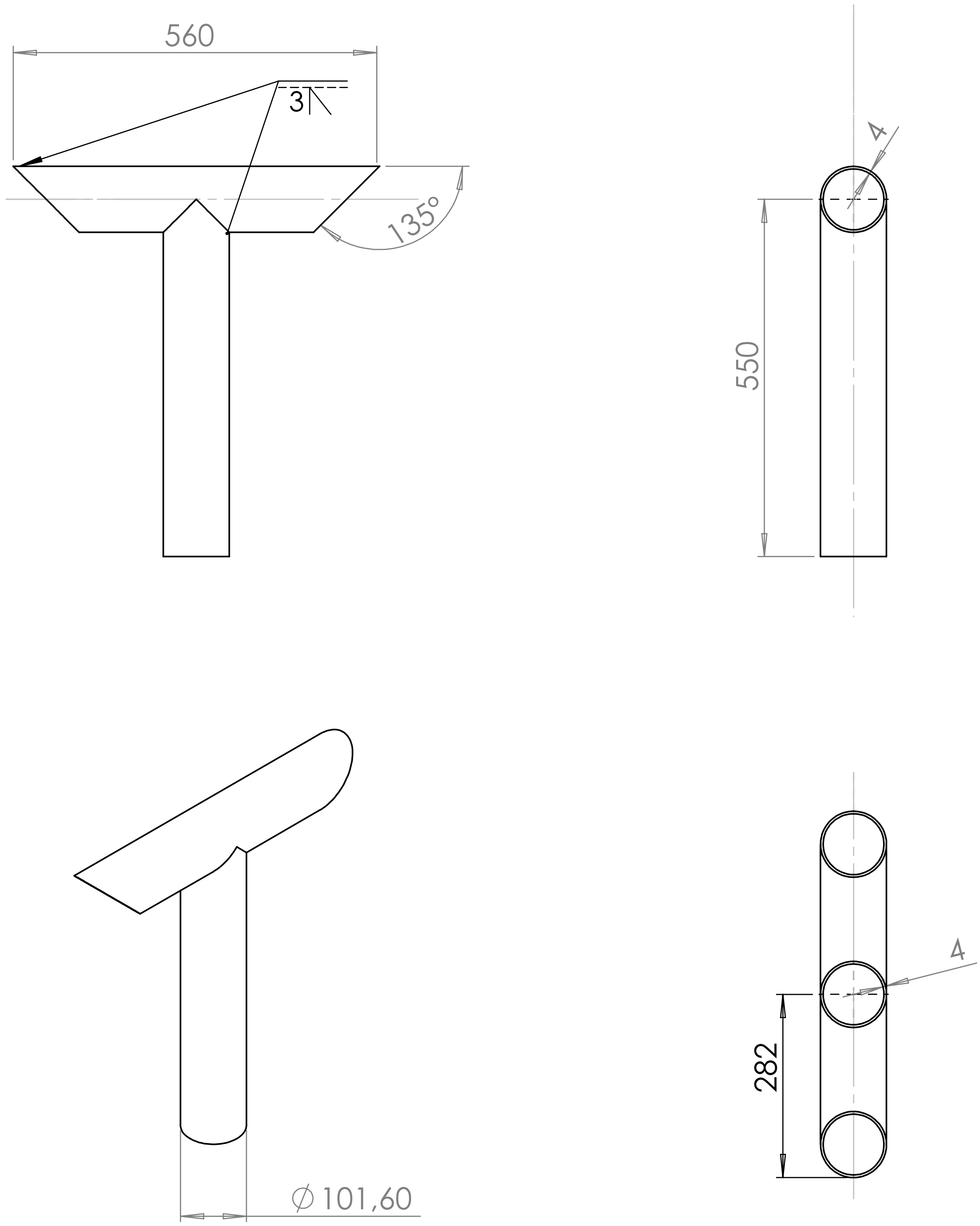
plates part for arm

DWG NO.27

A4

SCALE:1:5

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: Optim 500 MH
circular hollow section

WEIGHT:

TITLE:

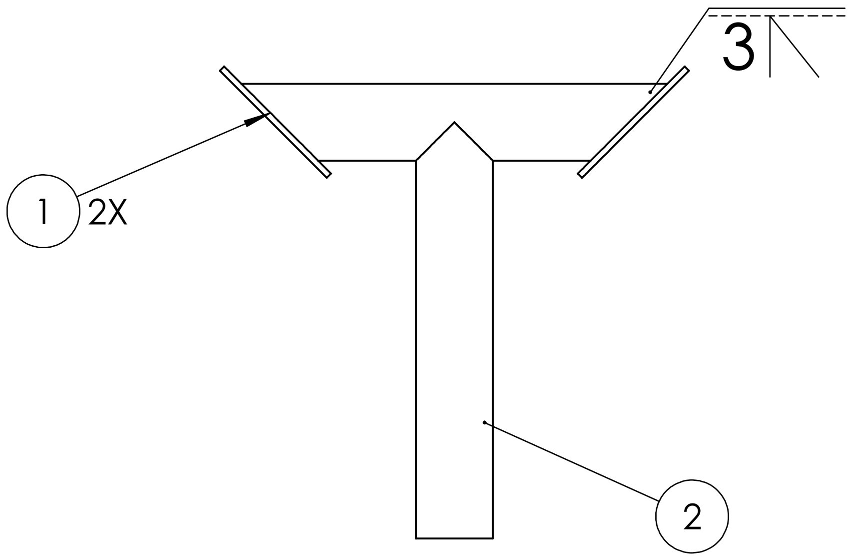
T-joint

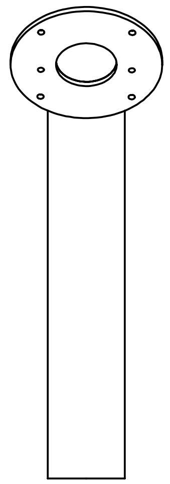
DWG NO.28

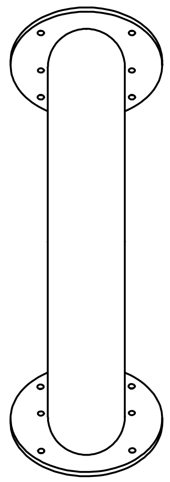
A4

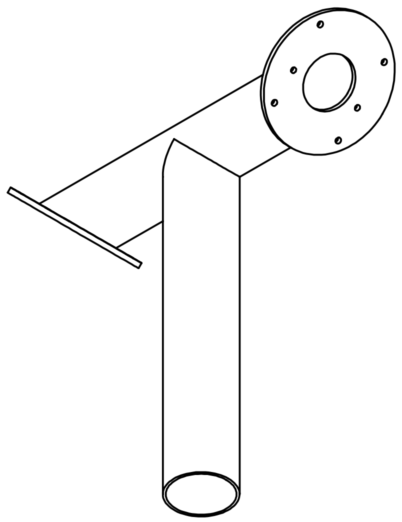
SCALE:1:10

SHEET 1 OF 1









1	plates part for arm
2	T-joint

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

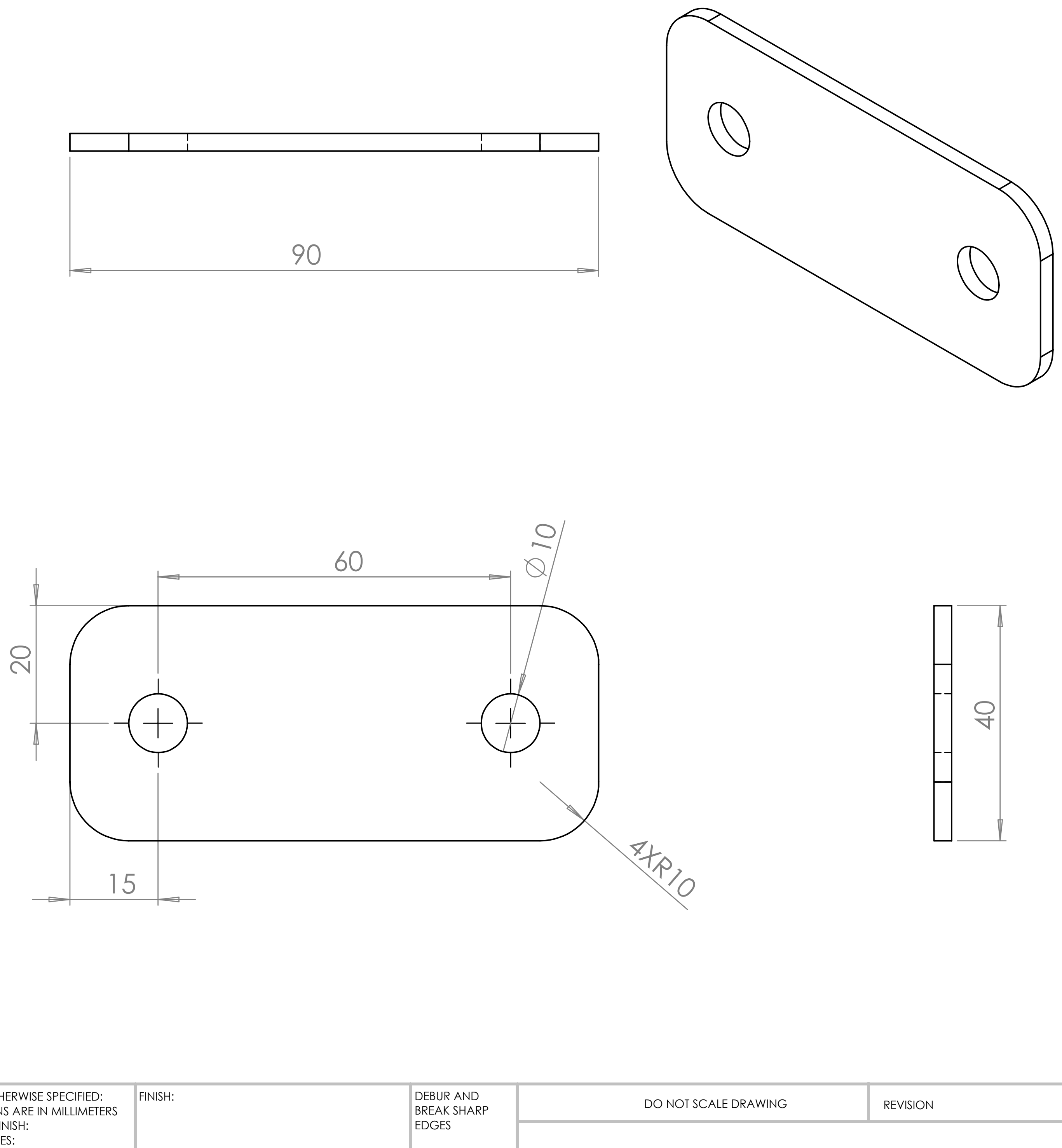
TITLE: T-joint Assem1

DWG NO.29

A3

SCALE:1:10

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: anglebeamconnecteted beamplate

MATERIAL:

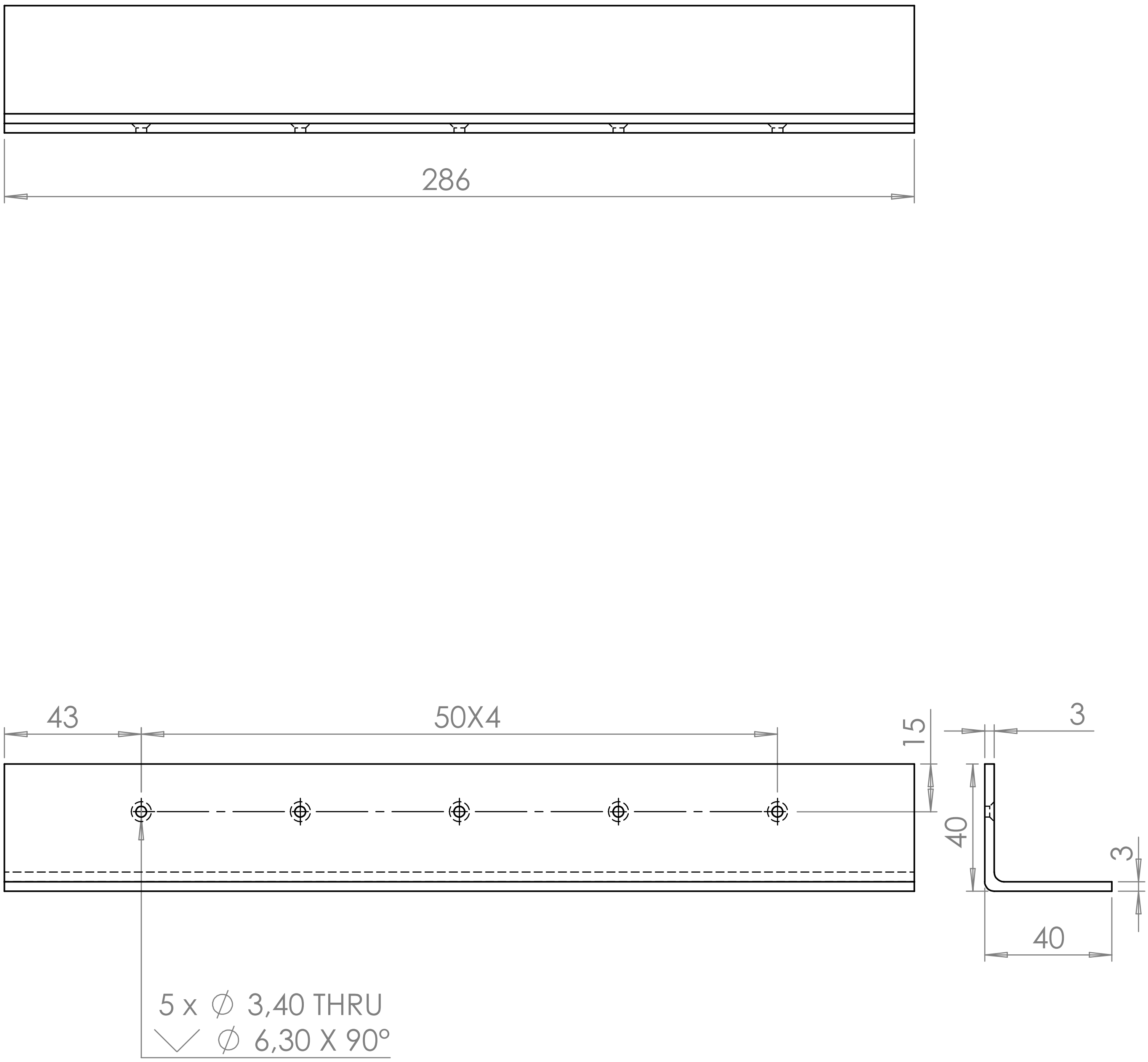
WEIGHT:

DWG NO.

A4

SCALE:1:1

SHEET 1 OF 1



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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

angleplateup tobattery

MATERIAL: Ruukki's cold-formed steel (equal angle)

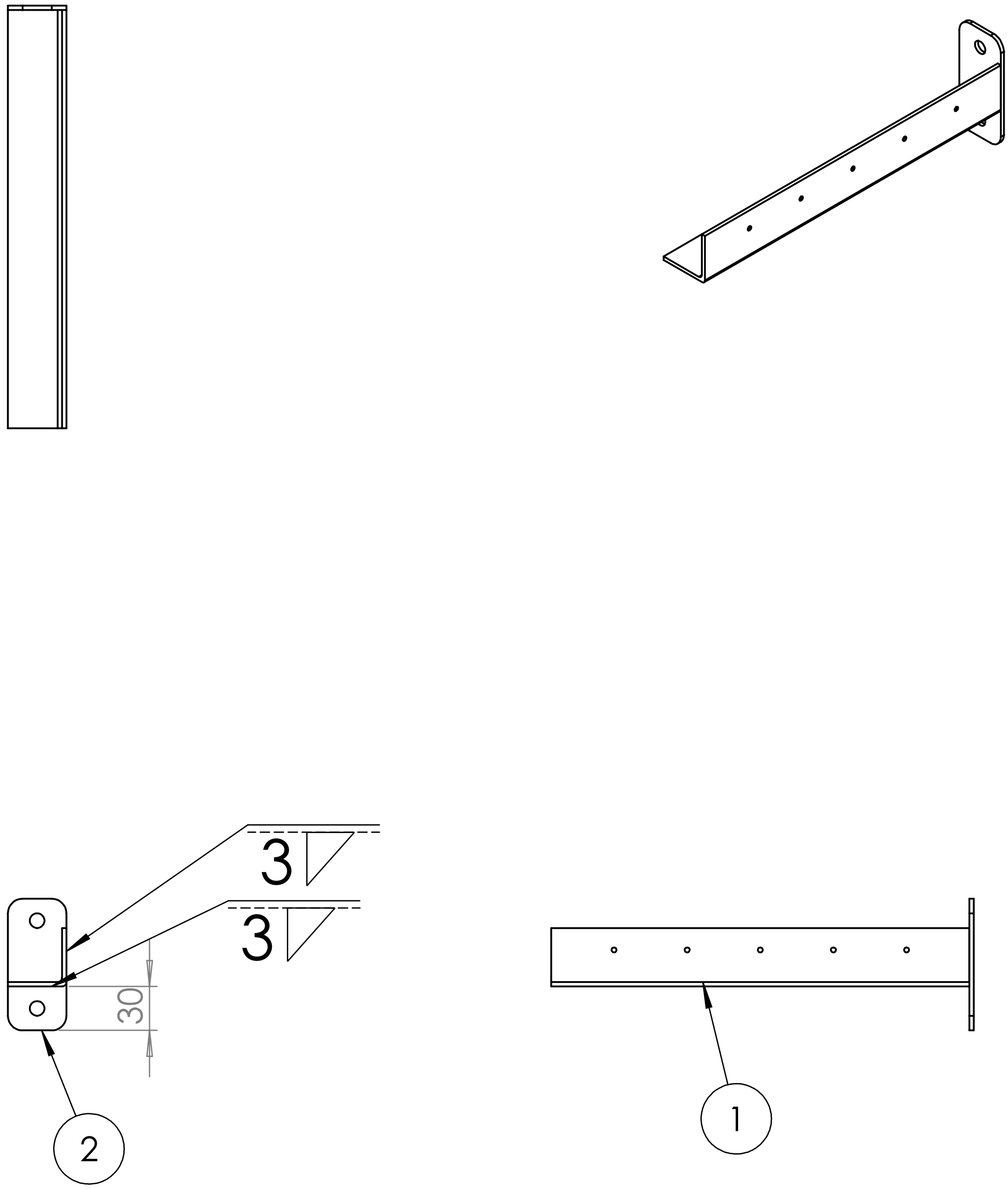
DWG NO. 30

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



1	angle plate up to battry
2	angle beam connected beam plate

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

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL:	
				WEIGHT:	

TITLE:

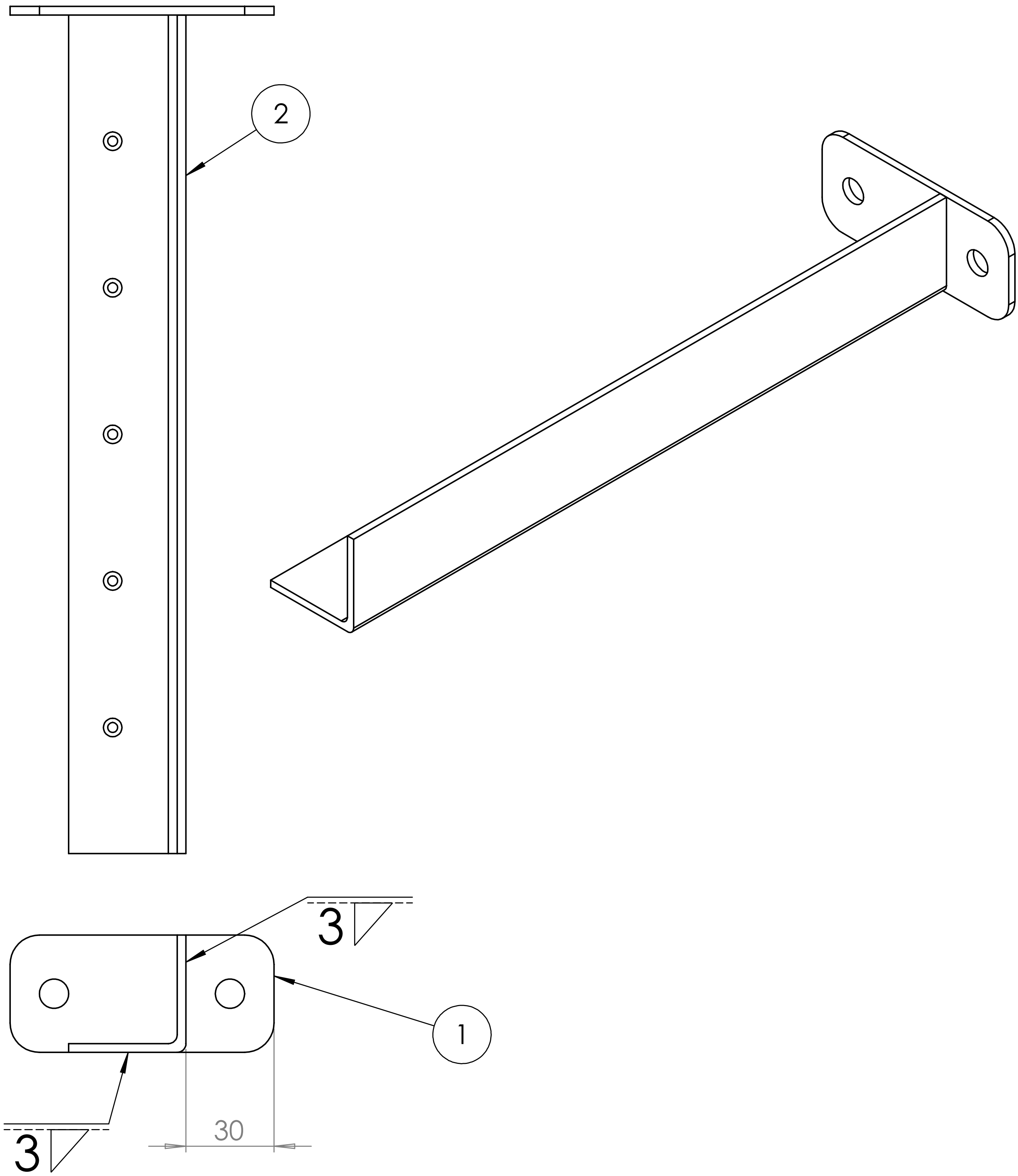
leftfuse partasembly

DWG NO. 31

A4

SCALE:1:5

SHEET 1 OF 1



2	angle plate up to battry
1	angle bam connected beam plate

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

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

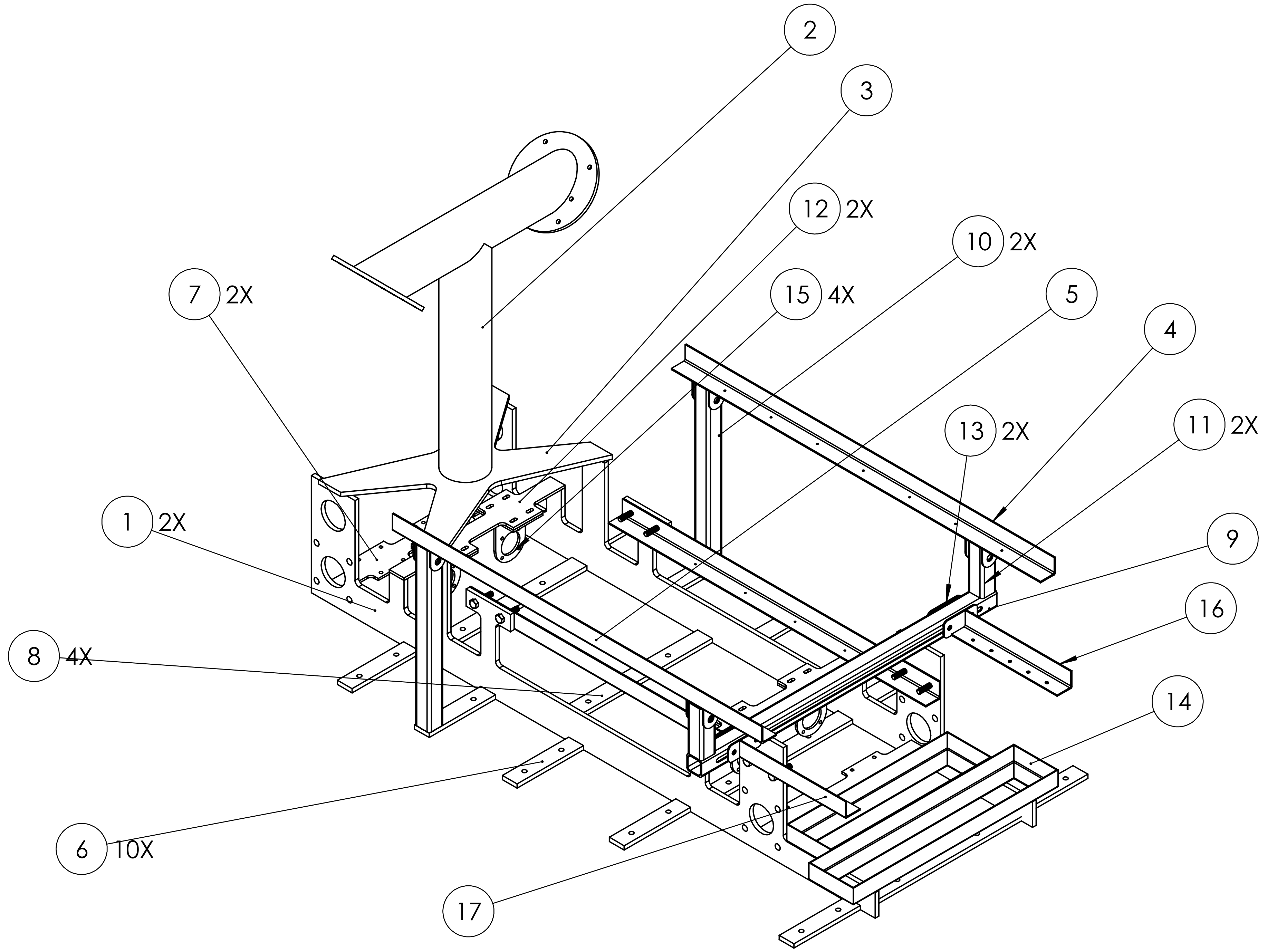
rightfuseanglebeampart

DWG NO. 20

A4

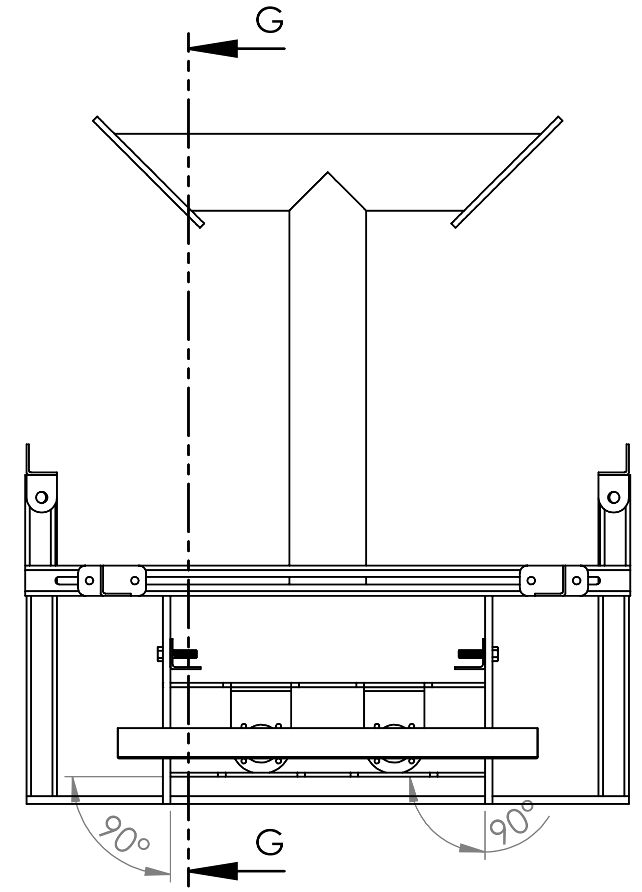
SCALE:1:5

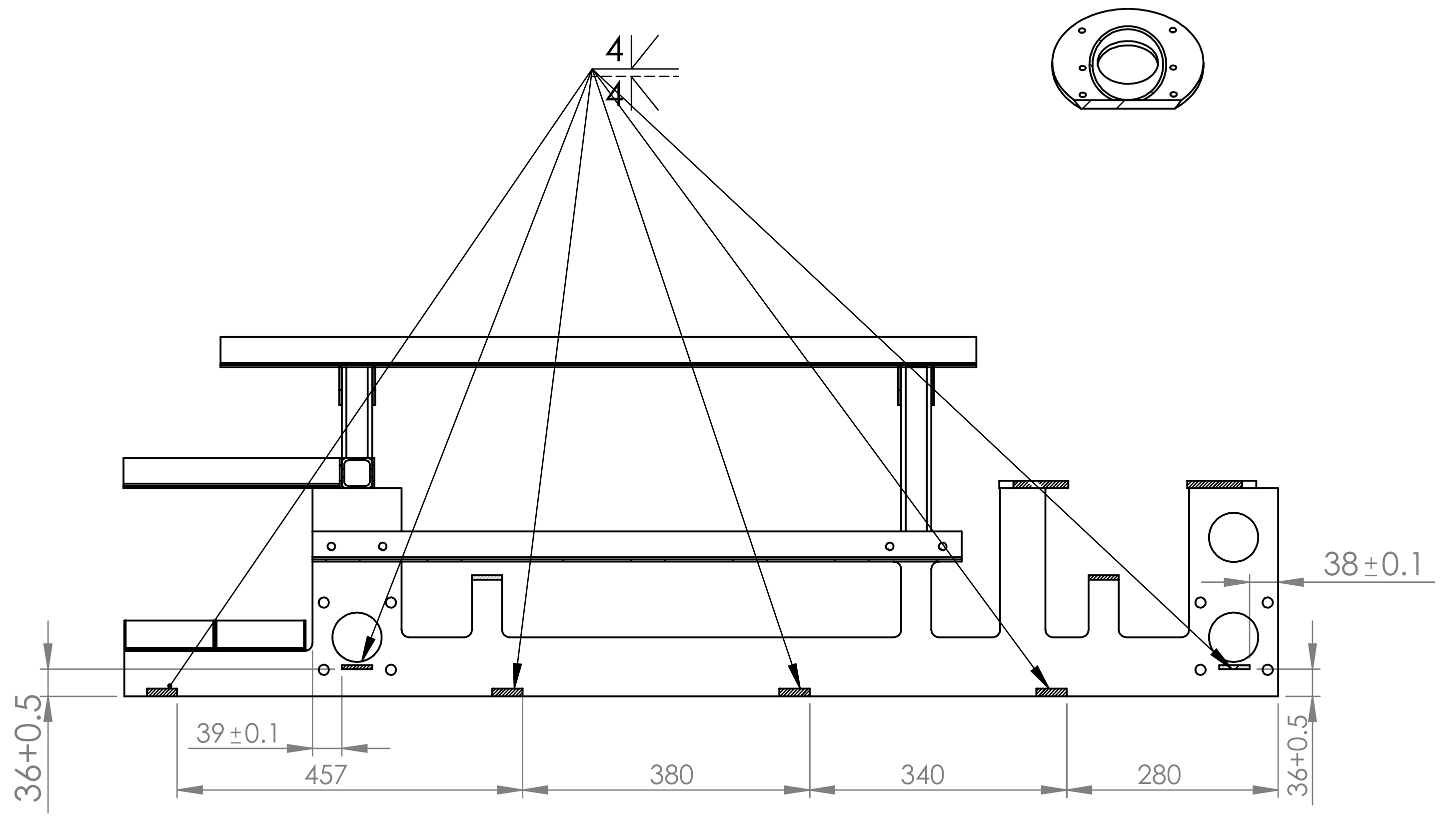
SHEET 1 OF 1



17	left fuse part assembly
16	rightfuseanglebeampart
15	motormounting assembly
14	complet battrybox
13	anglebeamconnected beam plate
12	motor mountuing plate beam
11	200mm40by40beam
10	425mm40by40 beam
9	800mm40by40 beam
8	middle platebeam
7	beveral gear
6	extension plate beam for controller
5	quadcopterleftsupport assembly
4	qadcopterrightsupport assembly
3	T-jount support
2	T-jointassem1
1	new plate beam

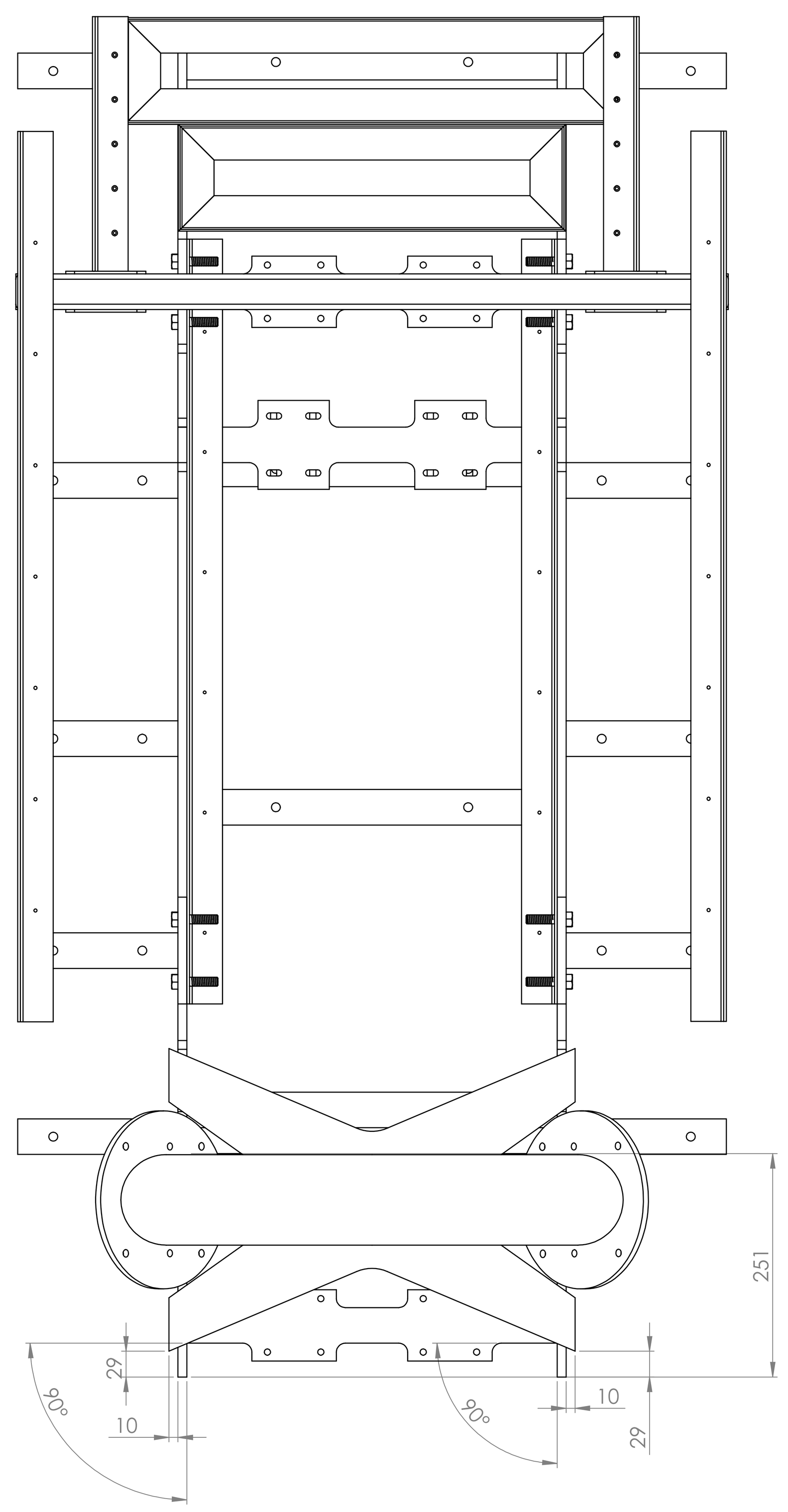
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN				frame assembly	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO.32	A3
			WEIGHT:	SCALE:1:10	SHEET 1 OF 1

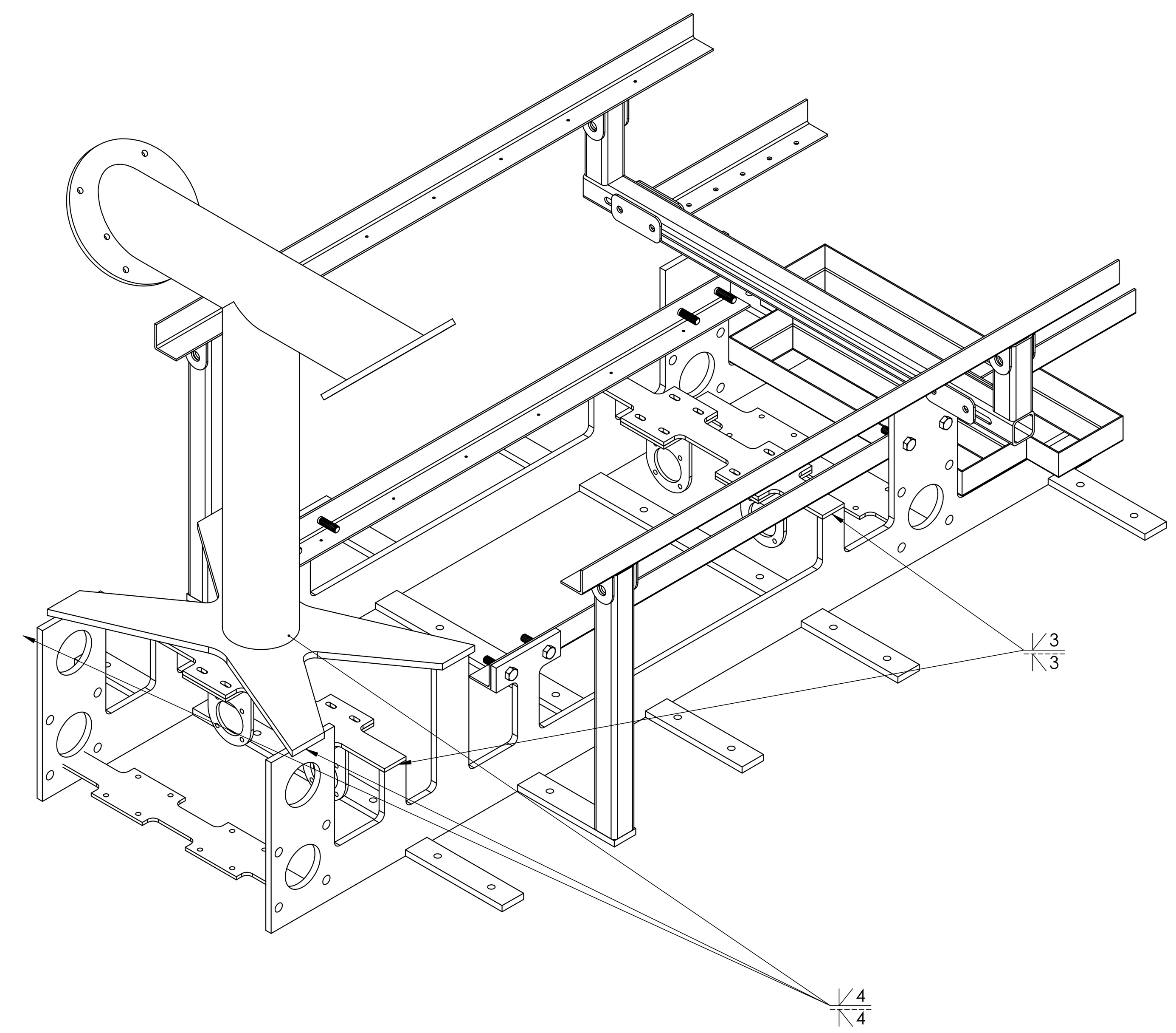


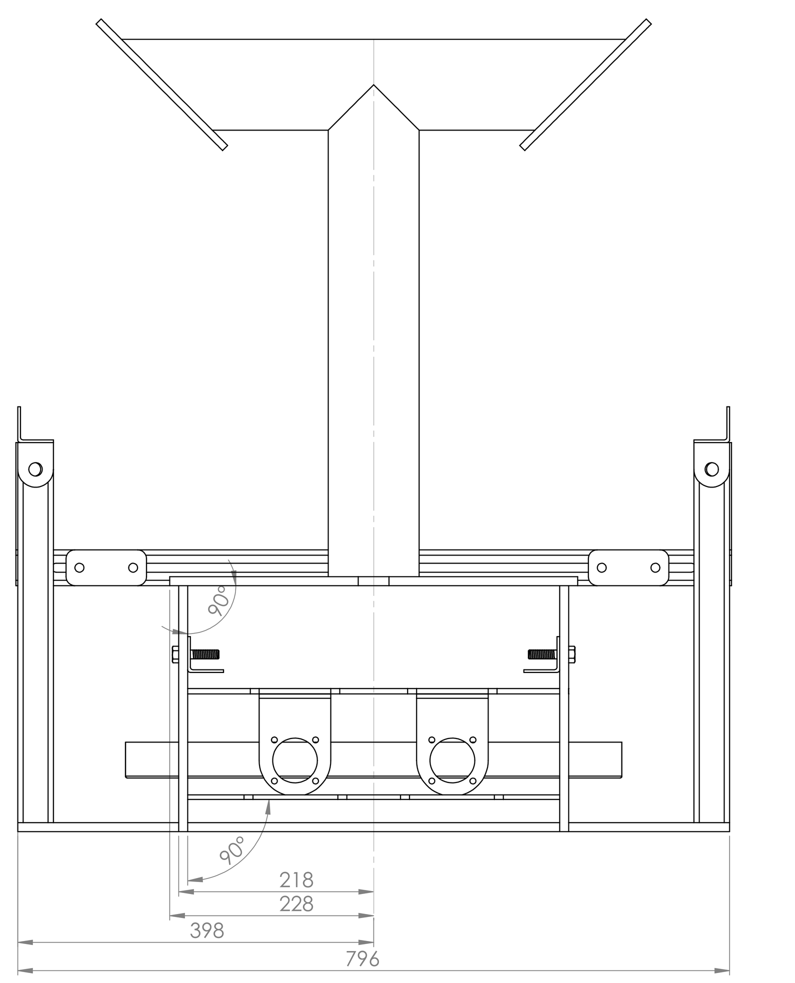


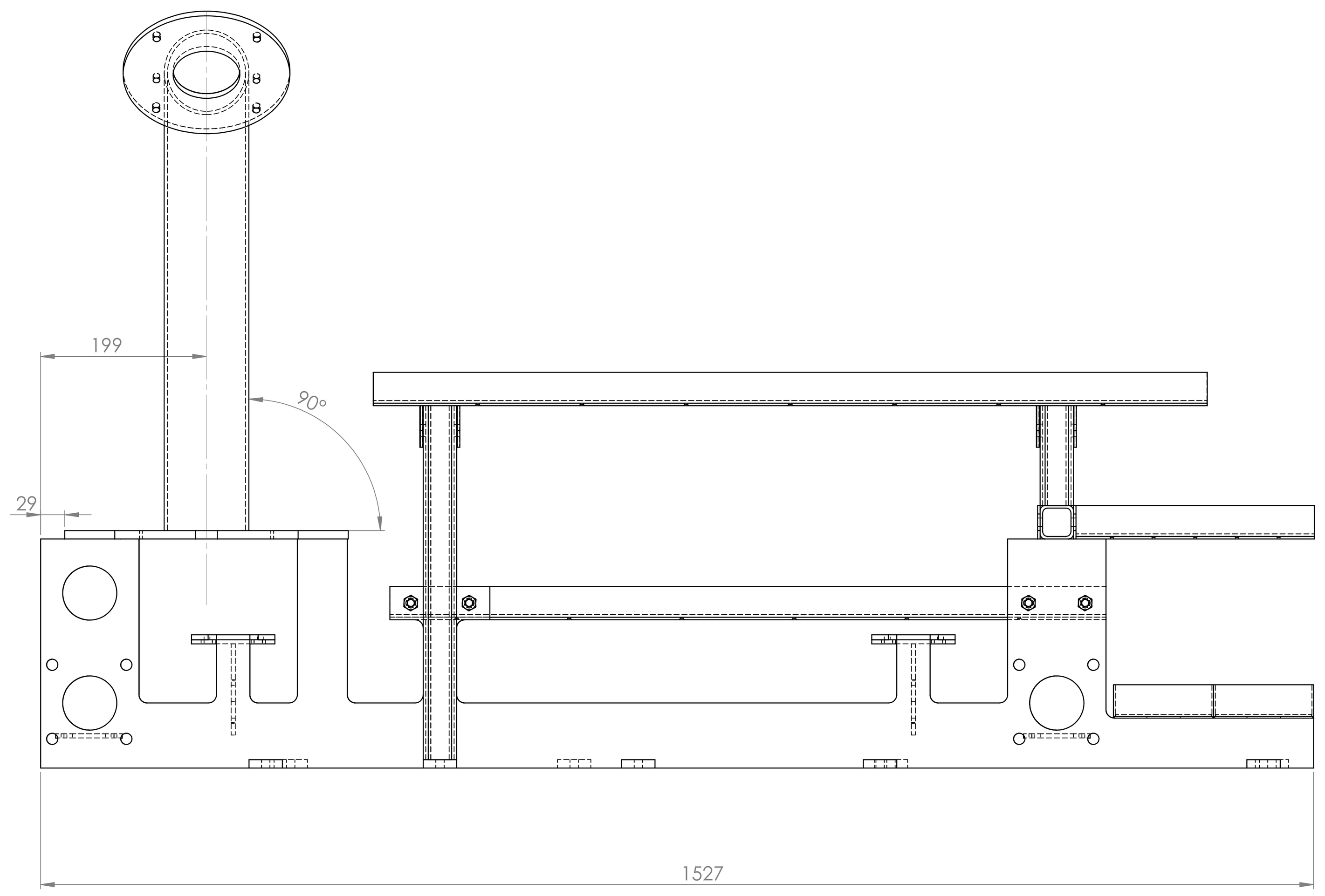
SECTION G-G
SCALE 1 : 10

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE: cut section for beveralgear support	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. 33	A3
				WEIGHT:	SCALE:1:20	SHEET 1 OF 1

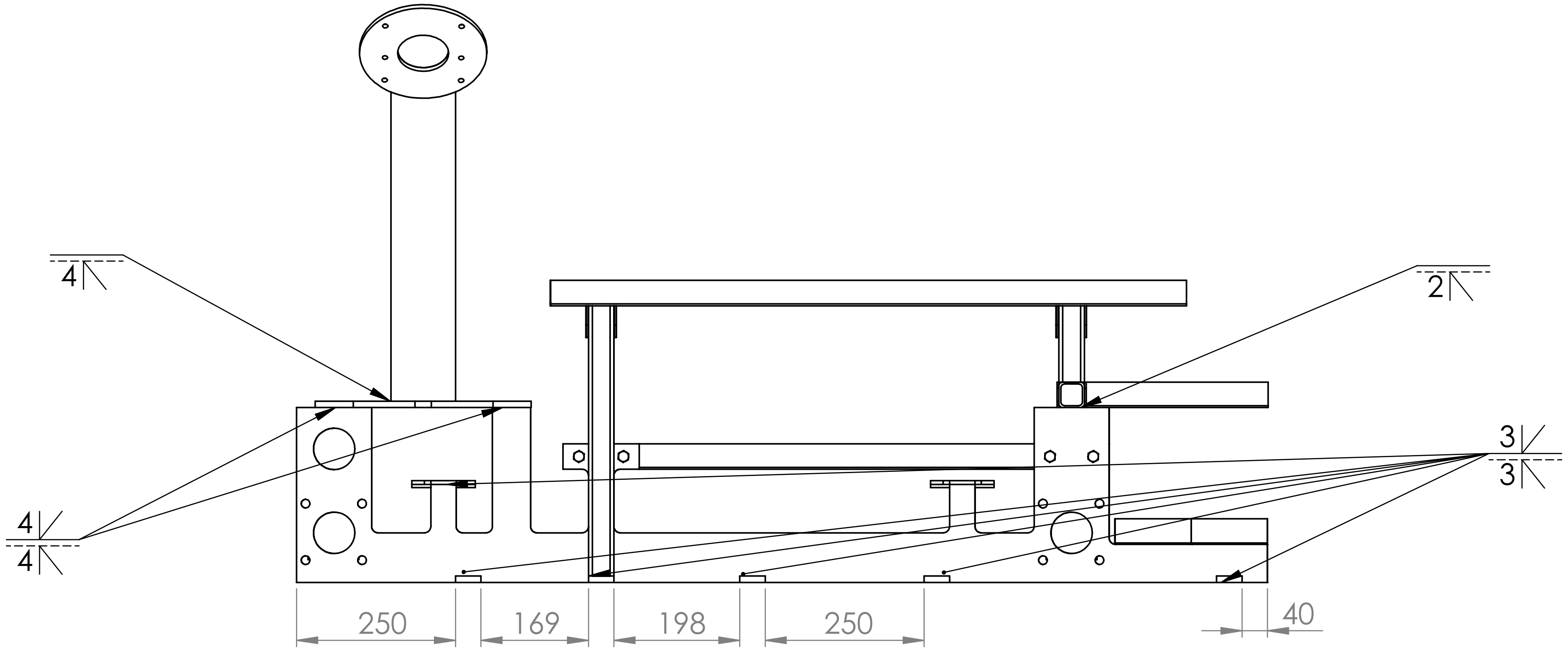


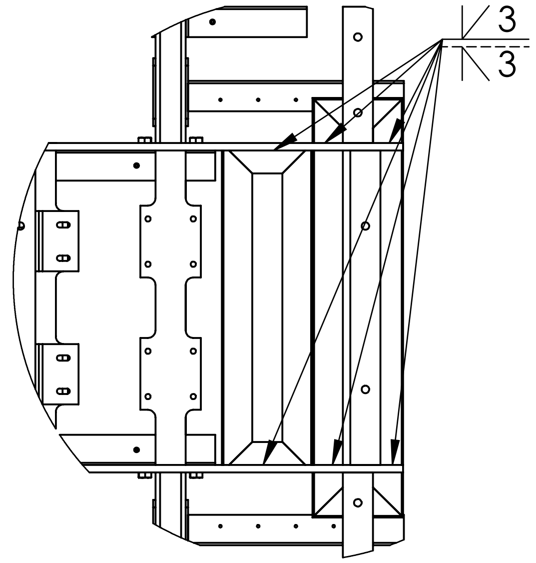






UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION		
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN						T-joint suport position+motor mounting beam position	
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. 34	A1
				WEIGHT:		SCALE:1:5	SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE		TITLE: welded joint on front side	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO.35	A3
				WEIGHT:	SCALE:1:20	SHEET 1 OF 1

Clearance holes chart

Machinery's Handbook 29th Edition

1610 CLEARANCE HOLES

Metric Fasteners.— The recommended drill and hole sizes for metric fasteners are tabulated in Table 2a. The minimum recommended hole is the drill size and the maximum recommended hole size is based on standard tolerances. The hole sizes for metric fasteners are in agreement with ISO 273, *Fasteners-Clearance Holes for Bolts and Screws*, except that ISO 273 covers fastener sizes M1 through M150.

Table 2a. Clearance Holes for Metric Fasteners *ASME B18.2.8-1999, R2005*

Nominal Screw Size	Normal			Close			Loose		
	Nominal Drill Size	Hole Diameter		Nominal Drill Size	Hole Diameter		Nominal Drill Size	Hole Diameter	
		Min.	Max.		Min.	Max.		Min.	Max.
M1.6	1.8	1.8	1.94	1.7	1.7	1.8	2	2	2.25
M2	2.4	2.4	2.54	2.2	2.2	2.3	2.6	2.6	2.85
M2.5	2.9	2.9	3.04	2.7	2.7	2.8	3.1	3.1	3.4
M3	3.4	3.4	3.58	3.2	3.2	3.32	3.6	3.6	3.9
M4	4.5	4.5	4.68	4.3	4.3	4.42	4.8	4.8	5.1
M5	5.5	5.5	5.68	5.3	5.3	5.42	5.8	5.8	6.1
M6	6.6	6.6	6.82	6.4	6.4	6.55	7	7	7.36
M8	9	9	9.22	8.4	8.4	8.55	10	10	10.36
M10	11	11	11.27	10.5	10.5	10.68	12	12	12.43
M12	13.5	13.5	13.77	13	13	13.18	14.5	14.5	14.93
M14	15.5	15.5	15.77	15	15	15.18	16.5	16.5	16.93
M16	17.5	17.5	17.77	17	17	17.18	18.5	18.5	19.02
M20	22	22	22.33	21	21	21.21	24	24	24.52
M24	26	26	26.33	25	25	25.21	28	28	28.52
M30	33	33	33.39	31	31	31.25	35	35	35.62
M36	39	39	39.39	37	37	37.25	42	42	42.62
M42	45	45	45.39	43	43	43.25	48	48	48.62
M48	52	52	52.46	50	50	50.25	56	56	56.74
M56	62	62	62.46	58	58	58.3	66	66	66.74
M64	70	70	70.46	66	66	66.3	74	74	74.74
M72	78	78	78.46	74	74	74.3	82	82	82.87
M80	86	86	86.54	82	82	82.35	91	91	91.87
M90	96	96	96.54	93	93	93.35	101	101	101.87
M100	107	107	107.54	104	104	104.35	112	112	112.87

Material description from Ruuki

1. Optim 900 QC plate property from Ruukkis.

Properties

Print

The Optim 900 QC steel grade meets the requirements of S900MC EN 10149-2. Correspondingly, Optim 960 QC meets the requirements of S960MC EN 10149-2. Optim 1100 QC has no equivalence with standard steels. The European standard EN 10149-2 (Hot rolled flat products made of high yield strength steels for cold forming - Part 2: Technical delivery conditions for thermomechanically rolled steels) forms the basis for the thermomechanical ultra high strength strip steels.

Wear resistance and hardness

The average hardness of Optim QC steel grades is high for structural steel, like over 300 HBW for yield strength of 900 MPa. In other words, twice the hardness of S355 structural steels. The high hardness and high strength indicate good wear resistance properties.

Materials testing

The Optim 900 QC and Optim 960 QC grades are tested according to EN 10149-1. So is the Optim 1100 QC grade, although the Re class 1100 MPa is not included in EN 10149-2.

Mechanical properties: tensile test

Optim QC steels. Tensile test.

Ruukki Optim	Yield strength $R_{p0.2}$ MPa Minimum	Tensile strength R_m MPa	Elongation Minimum A%
Optim 900 QC [1)]	900	930-1200	8
Optim 960 QC [1)]	960	980-1250	7
Optim 1100 QC [2)]	1100	≥1200	6

1) Yield and tensile strength are tested longitudinal to the rolling direction, but guaranteed both in the longitudinal and transverse direction. Elongation is tested longitudinal to the rolling direction.

2) Yield strength and tensile strength and elongation are tested transverse to the rolling direction.

Mechanical properties: Impact strength test

Optim QC steels. Impact strength test, longitudinal testing

Ruukki Optim	Temperature -40°C, energy level	Temperature -20°C, energy level
Optim 900/960 QC	27J minimum	(40J minimum)
Optim 1100 QC	NA	27J minimum

Impact strength is tested as Charpy V notch test in accordance with EN ISO 148-1:2010. The requirement values 27J and 40J mean test carried out with 10 x 10 longitudinal standard test pieces. With testing thicknesses less than 10 mm, the width of the test pieces corresponds with the strip thickness and the requirement values decrease in direct relation to the surface area of the test piece.

Chemical composition

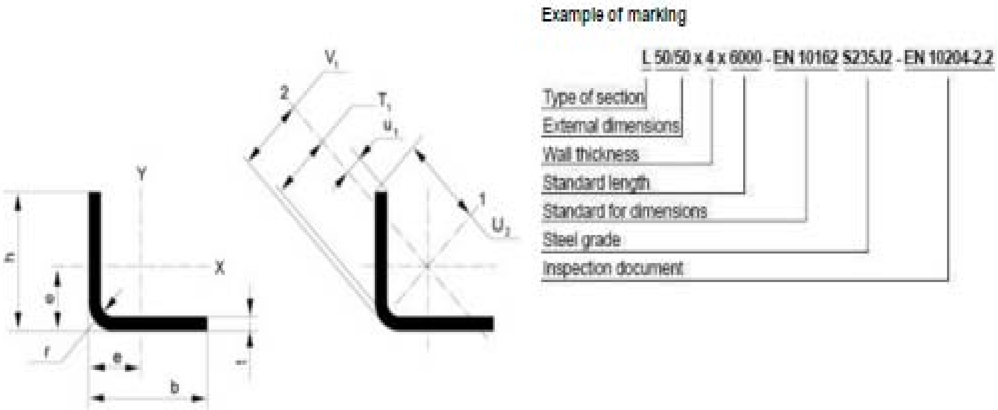
Maximum content % (cast analysis). The steel is fine grain treated.

Ruukki Optim	C	Si	Mn	P	S	Ti
Optim 900 QC	0.10	0.25	1.15	0.020	0.010	0.070
Optim 960 QC	0.12	0.25	1.20	0.020	0.010	0.070
Optim 1100 QC	0.16	0.30	1.25	0.020	0.010	0.070

2. Equal angle beam dimension

Compare Print

Dimensions



h	b	t	r	A	Au	M	X - X = Y - Y			1 - 1			2 - 2		
mm	mm	mm	mm	mm^2 x 10^2	m^2 /m	kg/m	I mm^4 x 10^4	W mm^3 x 10^3	i mm x 10	I mm^4 x 10^4	W mm^3 x 10^3	i mm x 10	I mm^4 x 10^4	W mm^3 x 10^3	i mmx 10
15	15	2	2	0.53	0.06	0.42	0.11	0.11	0.46	0.18	0.17	0.59	0.04	0.07	0.27
20	20	2	2	0.73	0.08	0.58	0.28	0.2	0.62	0.46	0.32	0.79	0.1	0.14	0.37
25	25	2	2	0.93	0.1	0.73	0.57	0.32	0.78	0.92	0.52	0.99	0.21	0.24	0.47
30	30	2	2	1.13	0.12	0.89	1	0.46	0.94	1.63	0.77	1.2	0.38	0.35	0.58
		3	3	1.65	0.12	1.3	1.42	0.67	0.93	2.32	1.09	1.19	0.51	0.48	0.56
40	40	2	2	1.53	0.16	1.2	2.45	0.84	1.26	3.96	1.4	1.61	0.94	0.66	0.78
		3	3	2.25	0.16	1.77	3.51	1.23	1.25	5.71	2.02	1.59	1.31	0.92	0.76
50	50	3	3	2.85	0.2	2.24	7.04	1.95	1.57	11.42	3.23	2	2.67	1.5	0.97
		4	4	3.74	0.2	2.93	9.06	2.54	1.56	14.76	4.18	1.99	3.36	1.88	0.95
60	60	3	3	3.45	0.24	2.71	12.39	2.84	1.89	20.03	4.72	2.41	4.74	2.22	1.17
70	70	5	6	6.57	0.27	5.16	31.53	6.29	2.19	51.31	10.37	2.8	11.7	4.72	1.34
75	75	4	4	5.74	0.29	4.5	32.07	5.89	2.36	51.9	9.79	3.01	12.23	4.58	1.46
80	80	5	6	7.57	0.31	5.94	47.81	8.29	2.51	77.65	13.73	3.2	17.98	6.33	1.54

A = Cross-sectional area   M = Weight   W = Section modulus

A_u = External area   I = Second moment of inertia   i = Radius of gyration