



MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

DESIGN OF A TEST BENCH FOR HIGH EFFICIENCY, LOW POWER ELECTRIC MOTORS OF COMPETITION VEHICLES

Autor: Carlos Moro García

Director: Luis Manuel Mochón Castro

Madrid

Agosto de 2022

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título
Design of a test bench for high efficiency, low power electric motors of
competition vehicles en la ETS de Ingeniería - ICAI de la Universidad Pontificia
Comillas en el
curso académico 2021/2022 es de mi autoría, original e inédito y
no ha sido presentado con anterioridad a otros efectos. El Proyecto no es
plagio de otro, ni total ni parcialmente y la información que ha sido tomada
de otros documentos está debidamente referenciada.



Fdo.: Carlos Moro García

Fecha: 20/ 08/ 2022

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Luis Manuel Mochón Castro

Fecha://

DISEÑO DE UN BANCO DE PRUEBAS PARA MOTORES ELÉCTRICOS DE ALTA EFICIENCIA DE VEHICULOS DE COMPETICIÓN

Autor: **Moro García, Carlos.**

Director: Jaensch, Malte / Mochón Castro, Luis Manuel.

Entidad colaboradora: TUfast eco y Technische Universität München.

RESUMEN DEL PROYECTO

INTRODUCCIÓN

Hoy en día la eficiencia de cada máquina empieza a tener más importancia, mientras que en el pasado la eficiencia quedaba relegada a un segundo plano y el objetivo principal era únicamente hacer una máquina que pudiera satisfacer las necesidades requeridas sin importar su eficiencia. Se está empezando a tener en cuenta tratar de minimizar la energía que se consume sea cual sea el proceso, con el objetivo de reducir nuestra huella de carbono. La razón de ello, es el calentamiento global y la falta de fuentes de energía. Por eso, se han producido algunos acuerdos internacionales como el inicio de la calificación energética europea o los Acuerdos Climáticos de París [1].

En relación con el cambio climático, se observa una tendencia a abandonar a largo plazo los combustibles fósiles. Y en este contexto ha aparecido la Shell Eco-marathon. Se trata de un programa académico centrado en la optimización de la energía que intenta apoyar el uso de soluciones energéticas nuevas y más limpias [5]. En esta tendencia, los motores eléctricos y las transmisiones híbridas están desempeñando un papel fundamental para un futuro concepto de movilidad sostenible y compatible con el medio ambiente.

Para el diseño y desarrollo de esta nueva generación de motores eléctricos se necesitan claramente el uso de los bancos de pruebas, donde se puedan obtener y analizar todos los parámetros eléctricos o mecánicos de un motor eléctrico. Los bancos de pruebas están diseñados para obtener todos los parámetros mecánicos y eléctricos de un motor como: par, velocidad, propiedades térmicas, puntos de sobrecarga, corrientes de cortocircuito, etc. En relación con esto, el objetivo principal de este trabajo va a ser desarrollar el diseño mecánico de un banco de pruebas para motores eléctricos. El usuario de este futuro banco de pruebas del proyecto será el equipo TUfast eco, que participa en la Shell Eco-marathon. En esta competición diferentes equipos universitarios construyen sus vehículos con el objetivo de hacer el coche lo más eficiente energéticamente posible sin dejar atrás que sea lo más rápido posible. Por lo tanto, hay una gran necesidad de un banco de pruebas para poder analizar a fondo cuál es el comportamiento real de su motor.

Además, en este proyecto el banco de pruebas que se va a construir, también debe ser compatible con la caja de cambios. Hacer que el banco de pruebas sea compatible con la

caja de cambios permitirá al equipo analizar también la eficiencia de su caja de cambios, lo cual es clave para su futuro desempeño en la competición.

Las principales limitaciones de este proyecto son: bajo presupuesto, el banco de pruebas debe ser lo más preciso posible, debe ser seguro para los estudiantes y compatible con la caja de cambios.

Estado del arte y tecnología

Existe una amplia gama de motores eléctricos que van desde los 250W de las bicicletas eléctricas hasta los 100kW de algunos vehículos eléctricos [6]. Esta es la razón por la que hay muchos tipos de bancos de pruebas en el mercado y por la que hay una gran necesidad de probar las características de toda esta amplia gama de motores durante su desarrollo para que sean lo más eficientes posible.

En el mercado existen actualmente muchos bancos de pruebas para diferentes propuestas: Motores de combustión, bancos de pruebas de trenes de potencia, bancos de pruebas de vehículos, bancos de pruebas de emisiones, etc. Pero para la propuesta de este proyecto, este documento se va a centrar en los bancos de pruebas de motores eléctricos.

Elementos de un banco de pruebas

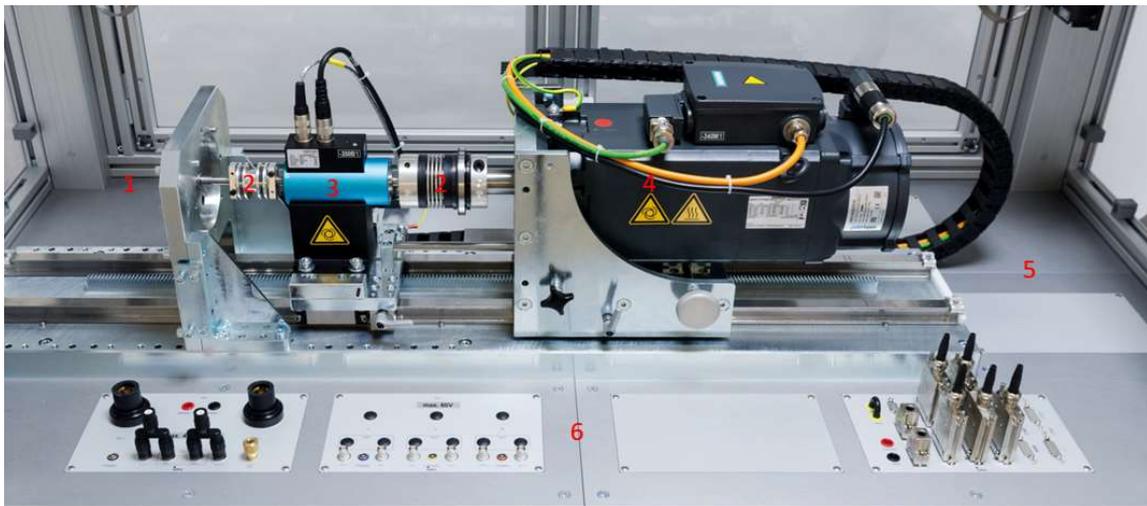


Figura 1: Elementos de un banco de pruebas

Un banco de pruebas se compone de varios elementos, como puede verse en la figura 1.

1. El elemento que falta en la figura y que está numerado como 1 es el motor eléctrico que se va a probar. Este elemento se suele denominar DUT (Device under test) y es el motor del que vamos a obtener todos los valores mecánicos y eléctricos que se persiguen en cada ensayo que se va a realizar. Este elemento es intercambiable dependiendo del motor que queramos analizar. Para el diseño de un banco de pruebas este es el elemento más importante ya que va a definir los parámetros mecánicos de diseño que va a soportar nuestro banco

de pruebas.

2. Estos son los acoplamientos y su función es conectar los ejes de la máquina de carga (número 4) y el DUT al sensor de par (número 3). Los acoplamientos son responsables de la transmisión del par, el movimiento y la potencia. Las pérdidas en ellos deben minimizarse en la medida de lo posible para que las mediciones realizadas desde el banco de pruebas sean lo suficientemente precisas. Por ello, también se encargan de aislar las posibles vibraciones y de compensar la desalineación que pueda haber entre los ejes y el eje del sensor de par. Existen tres tipos de desalineaciones como podemos ver en la Figura 2.

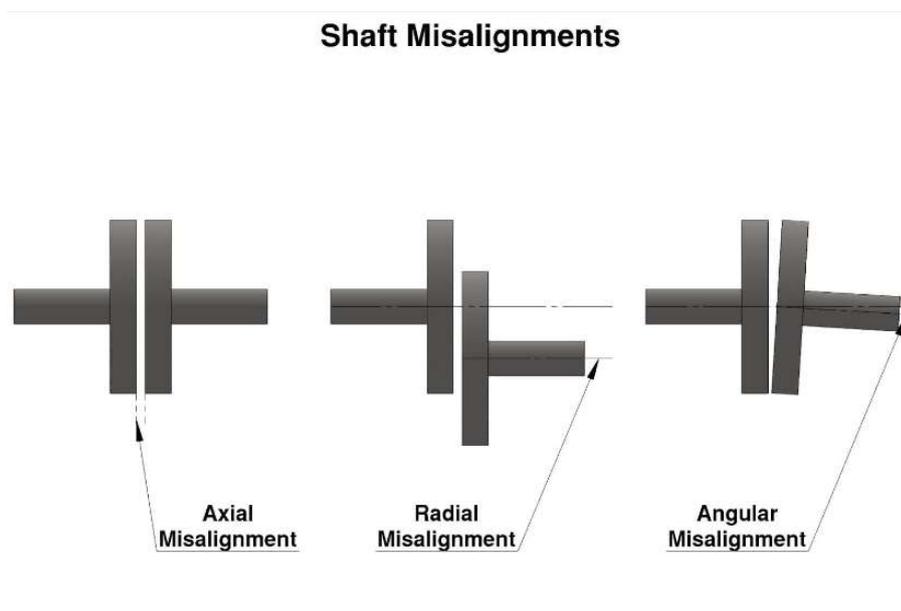


Figura 2: Tipos de desalineación

3. Este elemento es el sensor de par, que se encarga de adquirir todas las medidas de par, así como la velocidad en algunos casos. Es muy importante que nuestro sensor de par sea lo suficientemente preciso para la prueba que buscamos en nuestro banco de pruebas. Si no es así, las conclusiones que se extraigan del ensayo podrían ser erróneas.
4. Este último elemento es la máquina de carga también conocida como dinamómetro. La función del dinamómetro es la de actuar como carga mecánica para el DUT de forma que éste pueda ser probado en diferentes puntos de funcionamiento. Más adelante se explicarán todos los tipos de dinamómetros.
5. El número cinco representa el banco de pruebas propiamente dicho donde se monta todo. El banco de pruebas debe soportar todo el peso de los elementos que se van a montar encima y también tiene que aislar las vibraciones que van a producir la máquina de carga y el DUT.

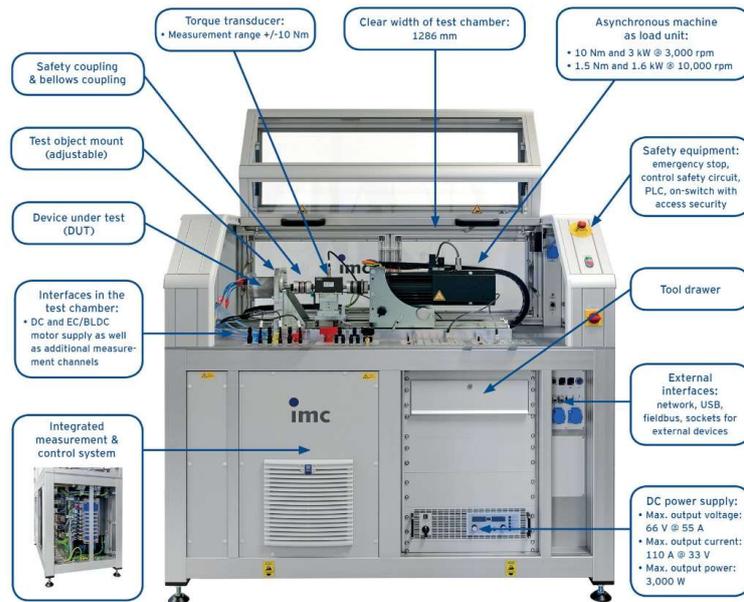


Figura 3: Test Bench example [7]

En la figura 3 se muestra un ejemplo de cómo sería un banco de pruebas completo. En la parte superior del banco se identifican fácilmente los principales elementos descritos anteriormente y en la parte inferior se alojan todos los dispositivos eléctricos y electrónicos.

La parte más importante de un banco de pruebas eléctrico es su dinamómetro. La función de este dinamómetro es actuar como un sistema de frenado para nuestro motor eléctrico. Según este dinamómetro los bancos de pruebas de motores eléctricos se dividen en dos tipos: dinamómetros pasivos y dinamómetros activos. Los primeros sólo se pueden utilizar para situaciones en las que nuestro banco de pruebas (DUT) sólo se va a utilizar como motor, este sería el caso de un motor de combustión. En este caso la única función del dinamómetro es disipar la energía mecánica del motor en forma de calor para frenar el motor. Para el segundo tipo se utiliza un motor eléctrico como dinamómetro, también llamado máquina de carga. En este caso la energía mecánica que proviene del DUT se transfiere en energía eléctrica a través de nuestra máquina de carga que está siendo operada como un generador. Por lo tanto, las pérdidas de energía se minimizan. Pero esta no es la principal ventaja de esta configuración. Con este tipo de configuración, nuestro DUT también puede ser probado como un generador sólo poniendo nuestra máquina de carga en modo motor.

En el mercado hay varias empresas de bancos de pruebas que ofrecen varias soluciones profesionales. Sin embargo, estos bancos de pruebas están realmente sobredimensionados para este proyecto. La mayoría oscilan entre 3 y 5 kW y los precios rondan los 50.000 euros para los dinamómetros pasivos, y entre 80.000 y 120.000 euros para un sistema de

dinamómetro activo [6]. El elevado precio de estos bancos de pruebas es una de las razones de este proyecto.

Funcionamiento de un banco de pruebas

Para el objetivo de este proyecto sólo se considerará la versión con dinamómetro activo. La alimentación para el ensayo proviene de la red en corriente alterna que luego es transformada en corriente continua por una fuente de alimentación de corriente continua. A través de este bus de corriente continua alimentaremos a los dos inversores, el de la máquina de carga y el DUT. Existen dos modos principales de control que pueden utilizarse indistintamente: en el primer modo se establece un par de referencia para la máquina de carga y una velocidad de referencia para el DUT, o viceversa. El modo más común es el primero, pero ambos serían posibles. Operando nuestro banco de pruebas de esta manera seríamos capaces de probar nuestro motor de pruebas en todos los puntos operativos que se deseen.

Por ejemplo: El DUT necesita ser probado a 3000rpm y 20Nm de par. Suponiendo que no hubiera pérdidas de energía, la máquina de carga se pondría a 20Nm de par en contra del giro y el DUT empezaría a girar a la velocidad deseada con un par positivo que compensará el contrapar de la máquina de carga.

Objetivo del proyecto

El objetivo principal del proyecto va a ser, poder diseñar un banco de pruebas que satisfaga todos los requisitos que exige el equipo de TUfast eco. Actualmente el equipo de TUfast eco está utilizando un motor con las siguientes especificaciones

- Max. Potencia 440W
- Par nominal 1,44N*m
- Par máximo 4,66N*m
- Velocidad máx. 7900rpm

Este banco de pruebas no va a ser diseñado sólo para un único motor eléctrico, sino que debe ser compatible con todos los posibles motores eléctricos que el equipo pueda utilizar en el futuro. Además, este banco de pruebas debe ser compatible con la caja de cambios del equipo. Esta característica no sería tan fácil ni barata de adquirir si el equipo quisiese comprarla en el mercado. Para lograr este objetivo hay que realizar un diseño mecánico específico.

Con las especificaciones del motor actual y sabiendo que: la velocidad máxima permitida para la competición es de 40Km/h, la relación de transmisión del equipo en promedio es $i=8$ y que el radio de la rueda es de 275mm. Es fácil deducir cuales serán los valores de los parámetros de diseño para el banco de pruebas en este proyecto. Por la seguridad de diseño y los posibles motores que se probarán en el futuro, los parámetros del diseño del banco de pruebas van a ser ligeramente sobredimensionados.

Ecuación 1

$$40 * 1.25 = 50 \frac{Km}{h} \text{ (safety factor for velocity)}$$

Ecuación 2

$$4.66 \rightarrow 5 Nm \text{ (safety factor)}$$

Ecuación 3

$$\left(\frac{50 \frac{Km}{h} * \frac{1000m}{Km} * \frac{1h}{3600s}}{0,275m} * 8 \right) * \frac{60s}{2 * 3.1416} = 3858 rpm \approx \mathbf{4000 rpm}$$

Ecuación 4

$$5Nm * 8 = \mathbf{40 Nm}$$

Estos son los valores para los que se va a diseñar el banco de pruebas. Como también tiene que ser compatible con la caja de cambios, utilizamos el valor máximo del par y de la velocidad. Estos valores máximos sólo se alcanzarán en el caso del par cuando la caja de cambios esté acoplada, para la velocidad cuando se quiera probar sólo el motor sin la caja de cambios acoplada.

Esto significa que el objetivo de este trabajo de fin de máster es diseñar un banco de pruebas con estos parámetros y además hacerlo asequible económicamente para el equipo, lo cual no es un objetivo sencillo ya que todos los bancos de pruebas que se ofrecen en el mercado son considerablemente caros. Por ello, para este proyecto también va a ser importante buscar los proveedores adecuados y compararlos.

Una dificultad adicional de este proyecto es que la precisión del banco de pruebas debe ser tan buena como la de uno comercial, ya que el objetivo principal del banco de pruebas es comprobar la eficiencia del motor eléctrico. Dado que la eficiencia de un motor eléctrico puede ser de hasta el 95%, sólo un error del 1% en las medidas podría llevar a conclusiones falsas. Para ello, hay que elegir bien los diferentes elementos del banco de pruebas y alinear bien todos los componentes para que no haya tensiones internas en el eje que desvirtúen las medidas.

El último objetivo es que el banco de pruebas esté preparado y sea adecuado para el uso de los estudiantes y que sea portátil. Esto significa que sea lo suficientemente sencillo y que sea seguro para su uso sin apenas conocimientos previos. Para este objetivo se van a tener en cuenta las diferentes normas de seguridad eléctrica para el diseño.

METODOLOGÍA

El plazo de este trabajo de fin de máster va a ser de 6 meses y seguirá cuatro fases principales. En la primera fase se realizará una investigación científica y se entenderá el funcionamiento de un banco de pruebas mediante la lectura de artículos científicos y diseños anteriores que se han realizado en el pasado. Mientras tanto, se identificarán los diferentes tipos de bancos de pruebas y también sus componentes mecánicos para que en la siguiente fase se puedan diseñar. En la segunda fase se elegirá un tipo de banco de pruebas y se iniciará el diseño del mismo seleccionando los primeros componentes principales. En la tercera fase se validarán y aprobarán todos los componentes seleccionados para los requisitos necesarios. Por último, se comprarán y montarán los componentes.

Para la realización de este proyecto la principal herramienta que se va a necesitar es el software SolidWorks para el diseño completo en 3D del banco de pruebas. Esto será útil para futuras mejoras y su montaje. Además se necesitará un manual de seguridad eléctrica y mecánica, así como algunas normas DIN para un correcto diseño mecánico del banco de pruebas.

RESULTADOS Y CONCLUSIONES

Casi toda la información relevante para el desarrollo, las pruebas y las medidas de un motor eléctrico se obtienen con un banco de pruebas. En la actualidad el equipo TUfast eco no dispone de un banco de pruebas para su desarrollo de nuevos prototipos y es crucial para desarrollar una buena nueva generación de coches, más aún teniendo en cuenta que la competición se basa en la eficiencia energética y no sólo en la potencia. Por ello, el equipo TUfast eco busca un banco de pruebas para sus futuras ediciones. No sólo eso, sino que el equipo TUfast eco quiere probar la caja de cambios del coche, que también es una parte muy importante en el diseño de un coche de alta eficiencia. Así que este banco de pruebas también tiene que ser también compatible con la caja de cambios del coche.

El proyecto de este banco de pruebas está dividido en tres trabajos que van a ser desarrolladas por tres estudiantes diferentes: la parte mecánica, la eléctrica y software de control. La elección de los componentes eléctricos fue realizada por otro estudiante que comenzó un mes después.

El objetivo de este trabajo de fin de máster era realizar el diseño de un banco de pruebas para motores eléctricos de baja potencia y alta eficiencia. El proceso de diseño mecánico del banco de pruebas se explica a lo largo de toda esta tesis de máster.

Este banco de pruebas fue diseñado como un banco de pruebas portátil que pudiera ser transportado. En cuanto a la estructura del banco de pruebas, se fabricó con perfiles de aluminio estándar y todo el sistema se construyó sobre una placa de acero con ranuras en T. Este banco de pruebas también cuenta con un sensor de par que toma las medidas, así

como con una máquina de carga. Para la protección de las piezas giratorias, también se incluyó una cubierta de acero en el diseño del banco de pruebas. En relación con la caja de cambios en este documento también se explica la pieza de adaptación para la caja de cambios para que ésta pueda ser instalada en el banco de pruebas.

También en este trabajo de fin de máster se ha tenido en cuenta el proceso de fabricación y los costes totales de la construcción ya que se quiere mantener el presupuesto lo más bajo posible. En el anexo de este documento se pueden encontrar los planos de fabricación de las piezas.

Este banco de pruebas permitirá al equipo tomar todas las medidas pertinentes que el equipo necesita y le ayudará a desarrollar mejores diseños mecánicos para las cajas de cambios, comparar diferentes soluciones de motores eléctricos y desarrollar también mejores controles de software para el motor.

El coste total estimado para la construcción mecánica de este banco de pruebas es de unos 8500 €. En el precio se incluyen todos los elementos principales y una estimación de los costes de material y fabricación de las piezas de diseño propio. La tabla 1 muestra los costes reales de cada pieza, los costes estimados para la fabricación de las piezas de diseño propio son de unos 500 €.

Tabla 1: Listado de precios

Nº	Component	Company	Model	Quantity	€/unity
1	15kW Mahle motor + Inverter	Mahle	Antriebssystem 48V 15kW ASV7102	1	1.828,80
2	IT enclosure	Rittal	Rittal 7507.110 19 Zoll	1	305,00
3	Coupling Load Machine	HBK	24/24mm	1	600,00
4	T-nutenplatte	Vakuumtisch.de	T-slot plate 10050	1	1.579,00
5	Vibrationsdaempfer	Paulstra	40x40	4	13,40
6	Scharnier	Pinet	50x50x2	2	14,30
7	Heat Sink		Sevcon Gen4	1	60,91
8	Coupling Load Machine	HBK	24/28mm	1	600,00
9	Torque Sensor	HBM	T22	1	2.000,00
10	Framework	Maytec	Several	1	873,00

Para los próximos pasos, el montaje y la fabricación del banco de pruebas propiamente dicho se llevarán a cabo una vez que las otras dos tesis estén terminadas. Después de que el banco de pruebas esté completamente montado, se realizará una prueba de todo el sistema y se comprobará si los resultados del diseño completo cumplen los requisitos de TUfast eco.

DESIGN OF A TEST BENCH FOR HIGH EFFICIENCY, LOW POWER ELECTRIC MOTORS OF COMPETITION VEHICLES

Author: **Moro García, Carlos.**

Director: Jaensch, Malte / Mochón Castro, Luis Manuel.

Cooperative entity: TUfast eco and Technische Universität München.

PROJECT SUMMARY

INTRODUCTION

Nowadays the efficiency of every machine is beginning to take more importance, whereas in the past the efficiency was relegated to a second level and the main objective was only to make a machine that could meet the required needs regardless of its efficiency. We are starting to take care not to waste any energy whatever the process may be, with the objective of reducing our carbon footprints. The reason being the global warming and lack of energy sources. This is why there has been some international agreements such as the beginning of the European energy rating or the Paris Climate Accords [1].

In connection with climate change, there is a noticeable trend towards a long-term shift away from fossil fuels. And in this context has the Shell Eco-marathon appeared. It is an academic program focused on energy optimization trying to support the use of new and cleaner energy solutions [5]. In this trend Electric motors and also hybrid drivetrains are playing a main role to a future sustainable and environmentally compatible mobility concept.

For the design and development of these new electric motor generation test benches are clearly needed, where you could get and analyze every electrical or mechanical parameter of an electric motor. Test benches are designed to obtain all the mechanical and electrical parameters of a motor such as: torque, speed, thermal properties, overload points, short-circuit currents and so on. In relation to this, the main objective of this work is going to develop the mechanical design of a test rig for electric motors. The user of this future test bench is going to be the TUfast eco team, who are taking part in the Shell Eco-marathon. In this competition different university teams build their vehicles with the objective of making the most energy efficient car possible. Therefore, there is a great need of a test bench to be able to analyze thoroughly what is the actual behavior of their motor.

Furthermore, in this project the test rig which is going to be built must also be compatible with the gear box. Making the test rig compatible with the gear box will allow the team as well to analyze how efficient their gear box is.

The main constraints for this project are: low budget, the test rig must be as accurate as possible, it must be safe for students use and compatible with the gear box.

State of science and technology

There is a very different wide range of electric motors that range from 250W for E-bikes up to 100kW for some E-vehicles [6]. This is the reason why there are many types of test stand solutions in the market and why there is a big need to test the characteristics of all this wide range of motors during its development so that they are as efficient as possible.

In the market currently it exists many different test rigs for different proposes: Combustion engines, powertrain test beds, vehicle test beds, emissions test beds, etc. But for the propose of this project, this document is going to focus on electric motor test beds.

Elements of an electric motor test bench

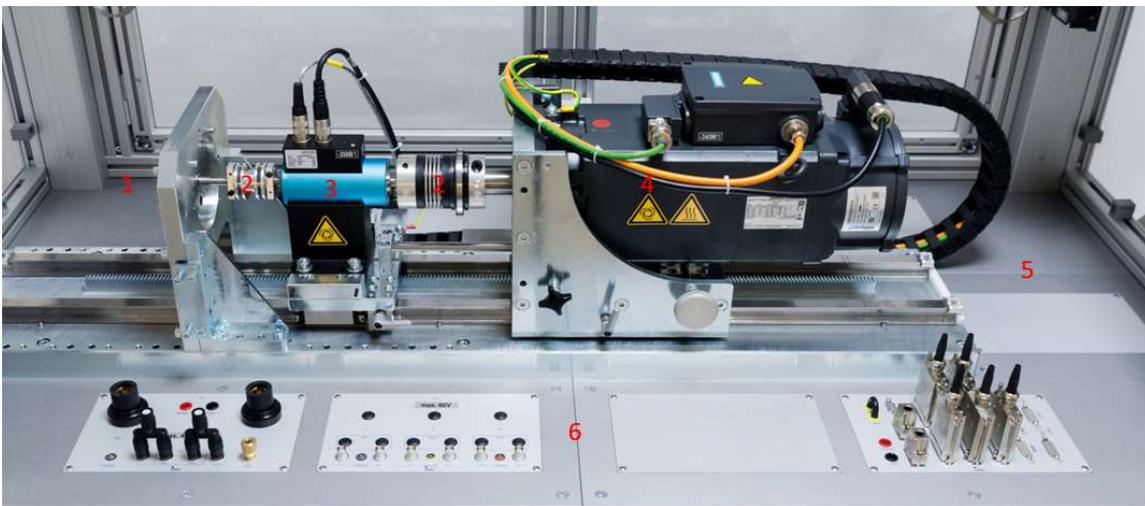


Figure 1: Elements of a test bench

A test bench is composed of several elements as it can be seen in the figure 1.

1. The element missing in the figure which is numbered as 1 is the electrical motor which is going to be tested. This element is usually referred as DUT (Device under test) and it is the motor from which we are going to obtain all the mechanical and electrical values, which are pursuing in each test that is going to be undergone. This element is interchangeable depending on which motor we want to test. For the design of a test bench this is the most important element as it is going to define the mechanical parameters that our test bench is going to withstand.
2. These are the coupling and the function of these is to connect the shafts of the loadmachine (number 4) and the DUT to the torque sensor (number 3). The couplings are responsible for the transmission of the torque, motion and power. The losses in these must be minimized if possible so that the measurements taken from the test bench are accurate enough. For this reason, they are also responsible for isolating plausible vibrations and compensating the minimal misalignment that

there might be between the shafts and the shaft of the torque sensor. There are three types of misalignments as we can see in Figure 2.

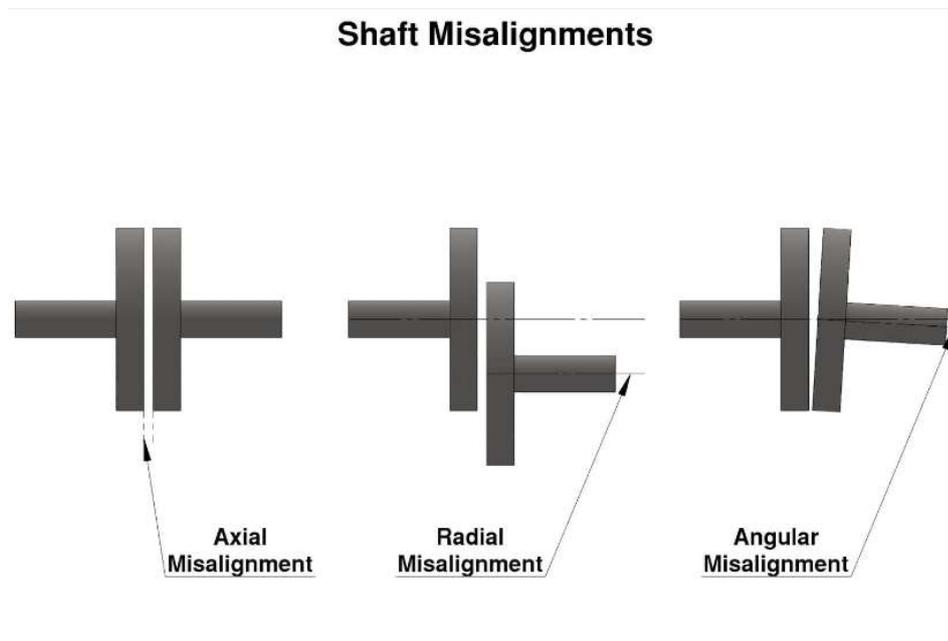


Figure 2: Misalignment types

3. This element is the torque sensor which is responsible for acquiring all the torque measurements as well as the velocity in some cases. It is very important that our torque sensor is accurate enough for the test that we are looking for in our test rig. If not the conclusions that are extracted from the test might be misleading.
4. This final element is the load machine also known as the dynamometer. The function of the dynamometer is to actuate as a mechanical load for the DUT so that the DUT can be tested in different operational points. Later on all the types of dynamometers will be explained.
5. Number five represents the test bench itself where everything is mounted. The test bench must withstand all the weight of the elements that are going to be mounted on top and it has also to isolate the vibrations that are going to be produced by the load machine and the DUT.

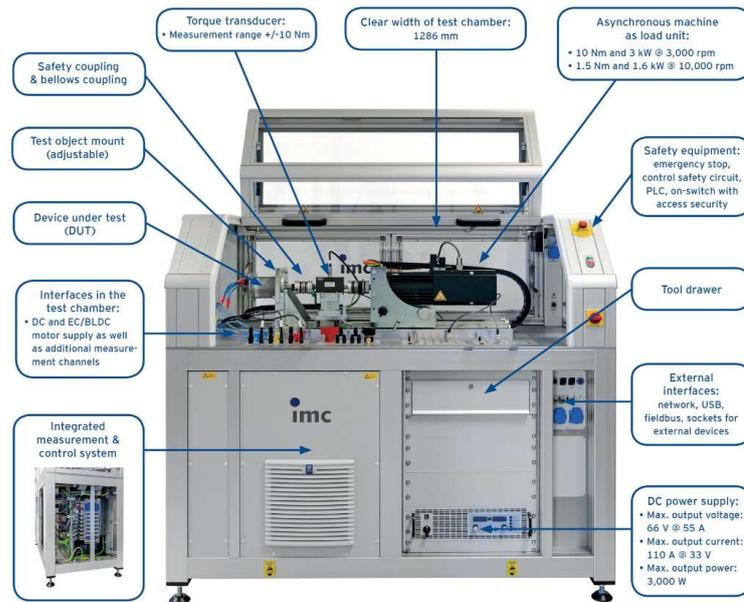


Figure 3: Test Bench example [7]

In the figure 3 there is an example of how a complete test bench would look like. The main elements that were previously described are easily identified in the top part of the stand and in the lower part all the electrical and electronical devices are housed.

The most important part of an electric test bench is its dynamometer. The function of this dynamometer is to act like a braking system for our electric motor. According to this dynamometer the electric motor test benches are divided into two types: passive dynamometers and active dynamometers. The first can only be used for situations where our test bench (DUT) is only going to be used as a motor, this would be the case for a combustion engine. In this case the only function of the dynamometer is to dissipate the mechanical energy from the motor in form of heat to break the motor. For the second type an electric motor is used as dynamometer, also called load machine. In this case the mechanical energy that comes from the DUT is transferred into electrical energy through our load machine which is being operated as a generator. Therefore, the energy losses are minimized. But that is not the main propose for this configuration. For this type of configuration our DUT can also be tested as a generator only by setting our load machine in motor mode.

In the market there are several test bench companies that offer several professional solutions. However, these test benches are really oversized for this project. The majority range from 3 to 5 kW and prices are around 50.000€ for passive dynamometers, and between 80.000€ and 120.000€ for an active dynamometer system [6]. The high price for these test benches is one of the reasons for this project.

Functioning of a test bench

For the objective of these project only the version with an active dynamometer will be considered. The power supply for the test comes from the grid in alternating current which is then transformed into DC by a DC power supply. Through this DC bus we will supply power to both inverters the inverter of our load machine and the DUT. There are two principal control modes which can be used indistinctively: in the first mode a reference torque is set to the loadmachine and a reference velocity for the DUT, or vice versa. The most common mode is the first one but both would be possible. Operating our test bench like this we would be able to test our test motor in every operational point that is desired.

For example: The DUT need to be tested at 3000rpm and 20Nm torque. Assuming there were no energy losses the load machine would be set to 20Nm counter torque and DUT would start rotating at the desired speed with a positive torque compensating the counter torque of the load machine.

Objective of the project

The main objective of the project is going to be able to design a test bench which satisfies all the requirements that are demanded by the TUfast eco team. At the moment the TUfast eco team are using a motor with the following specifications:

- Max. Power 440W
- Rated Torque 1.44N*m
- Peak Torque 4.66N*m
- Max. Speed 7900rpm

This test bench is not going to be designed just for a single electric motor but it must be compatible with all the future probable electric motors that team might use in the future. Furthermore, this test bench must be compatible with the gearbox of the team. This feature is not that easy and not cheap if the team would want to buy it in the market. To achieve this objective a through mechanical design must be done.

With the specifications of the actual motor and knowing that: the maximum permitted speed for the competition is 40Km/h, the gear ratio of the team on average is $i=8$ and that the radius of the wheel is 275mm. It is easy to deduct which will be the design parameter values for the test bench in this project. For the safety and future possible motors that will be tested, the parameters of the design of the test bench are going to be a over dimensioned.

Equation 2

$$40 * 1.25 = 50 \frac{Km}{h} \text{ (safety factor for velocity)}$$

Equation 2

$$4.66 \rightarrow 5 Nm \text{ (safety factor)}$$

Equation 3

$$\left(\frac{50 \frac{Km}{h} * \frac{1000m}{Km} * \frac{1h}{3600s}}{0,275m} * 8 \right) * \frac{60s}{2 * 3.1416} = 3858 rpm \approx \mathbf{4000 rpm}$$

Equation 4

$$5Nm * 8 = \mathbf{40 Nm}$$

These are the values for which the test stand is going to be designed for. As it needs also to be compatible with the gearbox, we use the maximum value of the torque and velocity. These values will only be achieved in the case of the maximum torque when the gearbox is coupled and velocity when we want to test just the motor.

This means that the aim of this master thesis is to design a test bench with these parameters plus making it affordable for the team which is not an easy task as all the test benches that are offered in the market are considerably more expensive. For this reason, in this project it is going to be also important to look for the right suppliers and compare them.

An extra difficulty of this project is that the precision of the test bench must be as good as a commercial one, the reason being that the main purpose of the test bench is to test the efficiency of the electric motor. As the efficiencies of an electric motor can be up to 95%, just a 1% error in the measures could lead to false conclusions. To achieve this the different elements of the test bench must be chosen thoroughly and the alignment of all the components must be done well so that there are not internal stresses in the shaft.

The last objective is that the test bench is ready and suitable for student use and it should be portable. This means that it is simple enough and that it is secure for its use without barely any previous knowledge. For this objective the different electrical safety rules are going to be considered for the design.

METHODOLOGY

The time frame for this master thesis is going to be of 6 months and it will follow four main phases. In the first phase there will be scientific research and understanding of how a test bench works by reading scientific papers and previous designs that have been done

in the past. In the meanwhile, the different types of test rigs will be identified and also its mechanical components so that in the next phase they can be designed. In the second phase a type of test bench is going to be chosen and the design of the test bench will be started by selecting the first main components. In the third phase all the components that were selected will be validated and approved for the requirements that are needed. Lastly the components will be bought and mounted.

For the accomplishment of this project the main tool that is going to be needed is the software SolidWorks for the complete 3D design of the test bench. This will be helpful for future improvements and its assembly. Additionally electrical and mechanical safety regulation manual are going to be needed as well as some DIN norms for a proper mechanical design of the test bench.

RESULTS AND CONCLUSIONS

Almost all of the relevant information for the development, testing and measures of a electric motor are obtained with a test stand. At the present time the TUfast eco team do no have a test stand for their development of new prototypes and it is crucial in order to develop a good new generation of cars, even more taking into account that the competition rely on energy efficiency and not just power alone. Therefore TUfast eco team is looking for a test stand for their future editions. Not only that but the TUfast eco team want to test the gearbox of the car which is also a very important part in the design for a high efficiency car. So this test stand has also to be compatible with the gearbox of the car.

The project of this test stand is divided in three thesis that are going to be developed by three different students: mechanical, electrical and software control. The selection of the electrical components was being done by another student who started one month later.

The objective of this master thesis was to do the design of a test stand for low power and high efficiency electric motors. The mechanical design process of the test stand is explained throughout this whole master thesis.

This test stand was design as a portable test stand that could be transported. Regarding the structure of the test stand it was made out of standard aluminium profiles and the whole system was built on top of a steel T-slot plate. This test stand also counts with a torque sensor taking the measures as well as a load machine. For the protection of the rotating parts, a steel cover was included as well in the design of the test bench. In relation to the gearbox in this document is also explained the adapter part for the gearbox so that the gearbox can be installed in the test stand.

Also in this thesis the fabrication process was taken into account and also the total costs of the construction as the budget is wanted to keep it as low as possible. In the annex of this thesis the fabrication drawings of the parts can be found.

This test stand will allow the team to take all the relevant measures that the team needs and it will help the team to develop better mechanical designs for the gearboxes, compare different electric motor solutions and develop as well better software controls for the motor.

The estimated total costs for the mechanical construction of this test stand are around 8500€. In the price is included all the principal element and an estimation of the material and fabrication costs of the own designed parts. The table 1 shows the actual costs for every part, the estimated costs for the fabrication of the own design parts are around 500€.

Table 1: Price List

N°	Component	Company	Model	Quantity	€/unity
1	15kW Mahle motor + Inverter	Mahle	Antriebssystem 48V 15kW ASV7102	1	1.828,80
2	IT enclosure	Rittal	Rittal 7507.110 19 Zoll	1	305,00
3	Coupling Load Machine	HBK	24/24mm	1	600,00
4	T-nutenplatte	Vakuumtisch.de	T-slot plate 10050	1	1.579,00
5	Vibrationsdaempfer	Paulstra	40x40	4	13,40
6	Scharnier	Pinet	50x50x2	2	14,30
7	Heat Sink		Sevcon Gen4	1	60,91
8	Coupling Load Machine	HBK	24/28mm	1	600,00
9	Torque Sensor	HBM	T22	1	2.000,00
10	Framework	Maytec	Several	1	873,00

For the future steps, the assembly and fabrication of the actual test stand is to be done, once the other two thesis are finished. Then after the test stand is completely mounted a testing of the whole system is to be done and check if the results of the complete design meet the TUfast eco requirements.

Contents

1	Introduction	1
1.1	Motivation	3
1.2	State of art	4
1.2.1	Elements of an electric motor test bench	4
1.3	Functioning of a test stand	7
1.4	Objectives	8
2	Dimensioning of the test stand	11
2.1	Mechanical requirements	11
2.2	Selection of principal elements	13
2.2.1	Dynamometer	13
2.2.2	Torque Sensor	18
2.2.3	Couplings	20
2.3	Test stand design	23
3	Elaboration of mechanical design	25
3.1	Trolley Design	25
3.2	Assembly parts of test stand	27
3.2.1	Load machine Bracket	28
3.2.2	Torque Sensor Platform	30
3.2.3	Test motor Interface-plate and Bracket	31
3.2.4	Cover	33
3.2.5	Gearbox holder	34
3.2.6	Wheelhub Flange	36
3.2.7	Inverter system	37
4	Detail of the design	39
4.1	T-slot plate	39
4.2	Dampers	41
4.3	Framework of the Trolley	41

4.4	Electrical enclosure	43
4.5	Inverter Heat Sink	44
4.6	Adapter test motor	45
5	Sustainable Development Goals	47
6	Conclusions and future work	49
A	Bill of Materials	51
A.1	Complete Bill of materials	51
A.2	Trolley bill of materials	52
B	Drawings	61
B.1	Own Design Parts	61
B.2	Test Motor Shaft	76
B.3	Wheelhub	78
	Bibliography	81

List of Figures

1.1	Evolution of CO2 concentration in the atmosphere	2
1.2	Number of electric cars available in the market	3
1.3	Principal elements of an electric motor test stand	4
1.4	Misalignment types	5
1.5	Complete Test Stand	7
1.6	Power flow	8
2.1	Four quadrant diagram	14
2.2	Mahle 15 kW motor	17
2.3	Load Cell type solution	18
2.4	Shaft Sensor and Flange Sensor	19
2.5	T22 torque sensor	20
2.6	Coupling types	22
2.7	Test bench	23
3.1	Ergonomic study about table height	26
3.2	Test stand design	27
3.3	Load machine Bracket	28
3.4	Subpieces Loadmachine Bracket	29
3.5	Torque Sensor Platform	30
3.6	Bottom view of Interface-plate torque sensor	31
3.7	Test machine Bracket	31
3.8	Interface Plate	32
3.9	Cover	33
3.10	Gearbox	34
3.11	Gearbox Platform	35
3.12	Gearbox Platform Inside View	36
3.13	Wheelhub Flange	36
3.14	Inverter Assembly	37
4.1	T-slot Plate	40

4.2	Framework of the Trolley	42
4.3	Handle of the Trolley	43
4.4	Framework Universal Connector	43
4.5	Rittal Enclosure	44
4.6	Heat Sink	45
4.7	Adapter test motor	46

List of Tables

- 2.1 Electric motors technology comparison 15
- 2.2 Motor comparison 16
- 2.3 Torque sensor comparison 19

- 4.1 T-slot plates Comparison 39

- 6.1 Price List 50

- A.1 Bill of materials 51

Chapter 1

Introduction

Climate change is one of the biggest issues in our current generation and one of the biggest challenges that the humanity has to affront. The current warming trend is of particular significance because it is unequivocally the result of human activity since the mid-20th century and proceeding at a rate that is unprecedented over millennia. There are several evidences and harmful consequences that our planet is suffering because of the global warming such as: The planet's average temperature has risen by 1 degree Celsius since the late 19th century, the Greenland ice sheets have decreased in mass on an average of 279 tons of ice per year since 1993, or that the sea level has increased in 20 cm in the last century, ... [1]

The main reason for this accelerated rise in the global temperature is the concentration of CO₂. It has been demonstrated that CO₂ is one of the biggest heat-trapping gasses in the atmosphere and it has been rapidly increasing during the last 75 years approximately, as it can be seen in the Figure 1.1.

In the late years there has been some measurements that have been made to stop this trend. In 2016 many countries around the world signed a plan route to reduce the global warming effect. This international agreement which is the Paris Climate Accords pursues to reduce the rise in the global temperature by a maximum of 2^o Celsius or preferably 1,5^o [2]. Also in connection with climate change, there is a noticeable trend towards a long-term shift away from fossil fuels. Not only because of its polluting effects but also due to the increase in its price, because the amount of cheap available fossil fuels is starting to lack.

One of the main sectors who is playing a big role in the global warming sector is the transport sector. The transport sector was responsible for 27% of the global production of CO₂ [3]. Because of this reason and that the governments are starting to increase the taxes on combustion engine cars and fuel, the automotive

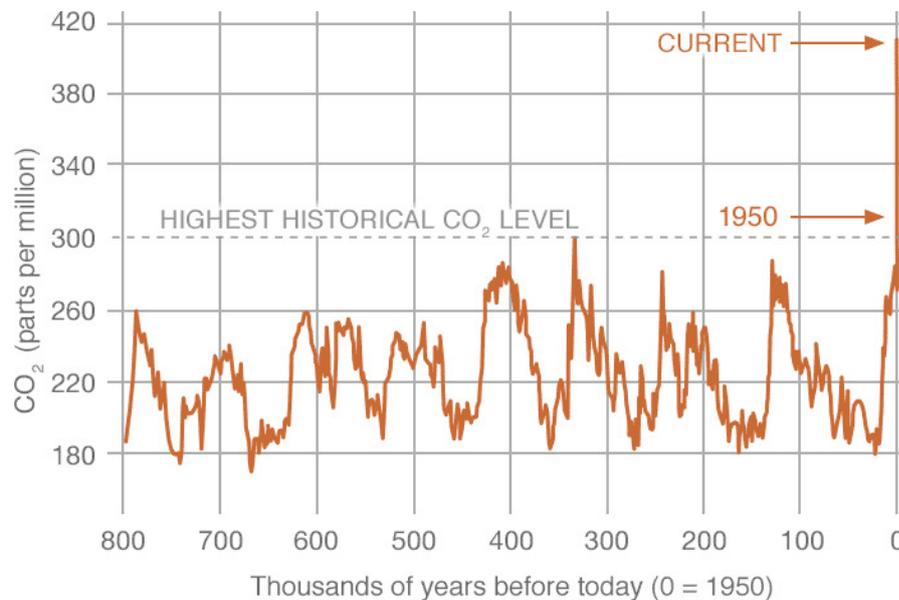


Figure 1.1: Evolution of CO₂ concentration in the atmosphere [1]

sector is clearly slowly changing towards a more electrified vehicle portfolio as it can be seen in the Figure 1.2.

This trend is making that the amount of money invested in the development of new generation electric motors is getting bigger. Nowadays the efficiency of every machine is beginning to take more importance, whereas in the past the efficiency was relegated to a second level and the main objective was only to make a machine that could meet the required power needs regardless of its efficiency. We are starting to take care not to waste any energy whatever the process may be, with the objective of reducing our carbon footprints.

In this context has the Shell Eco-marathon appeared. It is an academic competition focused on energy optimization trying to support the use of new and cleaner energy solutions and not wasting energy [5]. In this trend Electric motors and also hybrid drive trains are playing a main role to a future sustainable and environmentally compatible mobility concept. Hybrid and full electric power train architectures have proven to have a big potential to provide meaningful, innovative and sustainable solutions to the challenges mentioned before.

For the design and development of these new electric motor generation, test benches are clearly needed. Test benches provide the possibility to get and analyze every electrical or mechanical aspects of an electric motor. They are designed to obtain all the mechanical and electrical parameters of a motor such as: torque, speed, thermal properties, overload points, short-circuit currents etc.

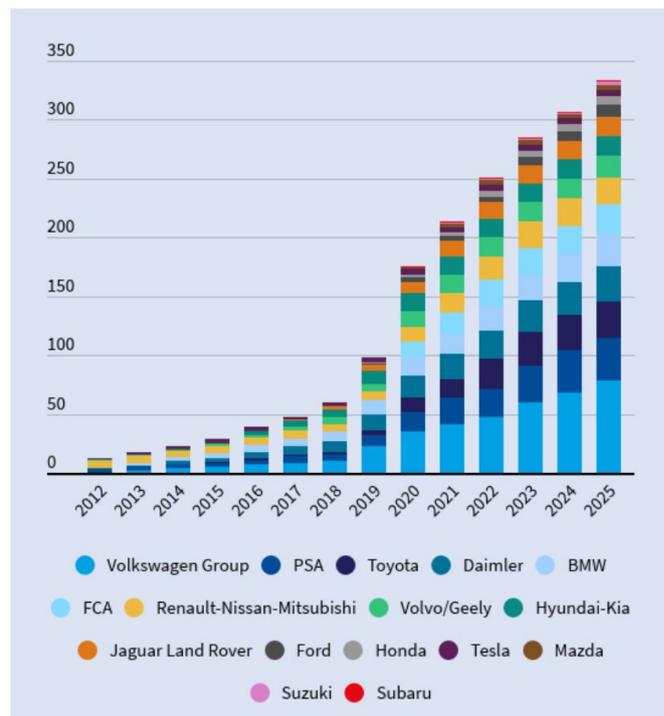


Figure 1.2: Number of electric cars available in the market [4]

1.1 Motivation

The main objective of this work is going to develop the mechanical design of a high precision test rig for low power electric motors. The reason for developing a new test stand and not buying one is because the solutions that are available in the market are either too expensive for the budget available or that their specifications are too big for the power of the motors that want to be tested in the team. Some test stand solutions can be up to 120000€ which is unaffordable for the budget of the team.

The user of this future test bench is going to be the TUfast eco team, who are taking part in the Shell Eco-marathon. In this competition different university teams build their vehicles with the objective of making the most energy efficient car possible. Therefore, there is a great need of a test bench to be able to analyze thoroughly what is the actual behavior of their motor.

The great advantage of having a test stand in the team is that many data can be collected from the motors. This would allow the team to analyse and compare the different motor solutions and selecting the best one for each future edition of the competition. Furthermore the test best would also allow the team to test their

motor control software in order to improve it and look for the weak operation points of their software. Also for the propose of this project the efficiency of the gearbox is going to be tested in this test rig. This is also one of the reasons why the team needs to develop its own test rig instead of buying it, so that their gear box can be installed and that it is also compatible with multiple electric motors.

1.2 State of art

In the market there exists many different test rigs depending on its propose: combustion engine test beds, power train test beds, vehicle test beds, emissions test beds... But for the propose of this project, this document is going to focus on electric motor test beds.

There is a very wide different range of electric motors that range from 250W for E-bikes up to 100kW for some E-vehicles [6]. This is the reason why there are many types of test stand solutions in the market and why there is a big need to test the characteristics of all this wide range of motors during its development so that they are as efficient as possible.

1.2.1 Elements of an electric motor test bench

In this subsection the principal elements of an electric motor test bench are going to be enumerated and explained. In the Figure 1.3 all the elements of a test stand can be seen with its corresponding numbers.

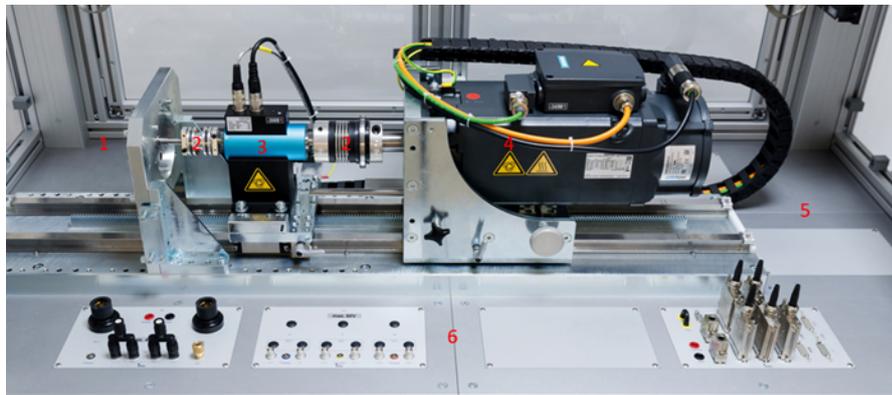


Figure 1.3: Principal elements of an electric motor test stand

1. **Test Motor:** The only element missing in Figure 1.3 is the electrical motor which is going to be tested. This element is usually referred as DUT (Device under test) and it is the motor from which we are going to obtain all the

mechanical and electrical values, which are pursued in each test that is going to be undergone in the test bench. This element is interchangeable depending on which motor is needed to be analyzed. For the design of a test bench this is the most important element as it is going to define the mechanical parameters that our test bench must withstand.

- Coupling:** These are the couplings of the test stand. The function of these is to connect the shafts of the load machine (number 4) and the DUT to the torque sensor (number 3). The couplings are responsible for the transmission of the torque, motion and power throughout the whole system. They try to minimize the losses in the transmission so that the measurements taken from the test bench are accurate enough to extract trustworthy conclusions. For this reason, they are responsible for isolating plausible vibrations and compensating the minimal misalignments that there might be between the shafts, which are responsible for these energy losses. There are three types of misalignments that the couplings must compensate. This misalignments can be seen in the Figure 1.4.

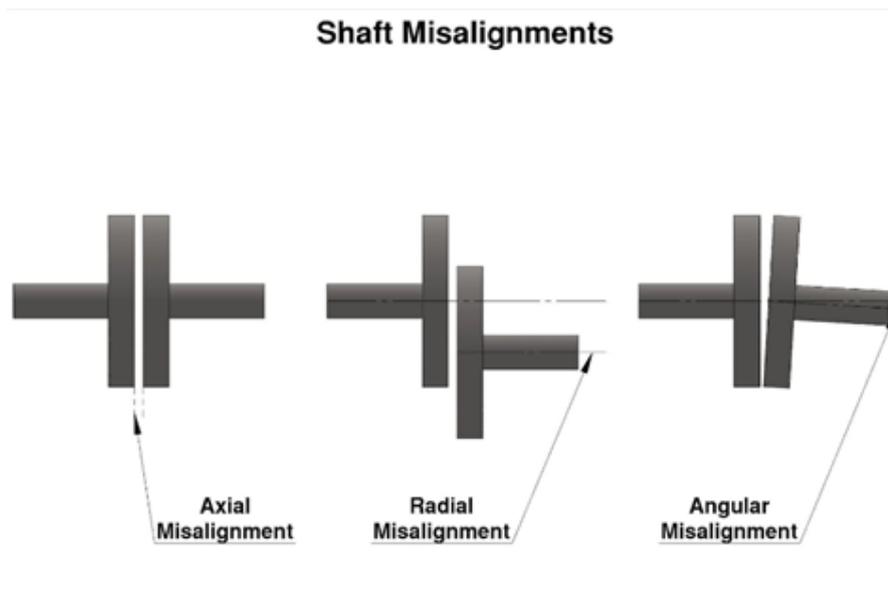


Figure 1.4: Misalignment types

- Torque sensor:** This element is the torque sensor which is responsible for acquiring all the torque measurements as well as the velocity in some cases in every time step. It is very important that our torque sensor is accurate enough for the tests that we are looking for in our test rig. Acquiring an excessive precise torque sensor would be too expensive, but it must at

least meet the prospects for which the test stand is thought for. If not the conclusions that are extracted from the test might be misleading. There are several types of torque sensor with different technologies, which will be discussed later on in the thesis. Some of them they are also capable of acquiring the velocity of the shaft, if not an extra velocity sensor would be needed or the velocity could be directly measured from the motor shaft.

4. **Load machine:** This final element is called the load machine. In many other test stands it would be called dynamometer but for the case of the electric motor test stands, it is more common the first term. The function of the load machine is to actuate as a mechanical load by applying a counter torque against the DUT so that the DUT can be tested in different operational points. Later on all the types of dynamometers will be explained.
5. **Stand:** Number five represents the test bench itself where everything is placed. The test bench must withstand all the weight of the elements that are going to be mounted on top and it has also to isolate the vibrations that are going to be produced by the load machine and the DUT.
6. **Control Panel:** The function of the control panel is to regulate the velocity and torque at which our test is going to be carried out. In this case, as it can also be seen in the Figure 1.3, the power supply and the data acquisition is also situated next to the control panel.

In the Figure 1.5, there is an example of how a complete test bench would look like. The main elements that were previously described are easily identified at the top part of the stand and in the lower part all the electrical and electronic devices are housed. In this test stand there is also on top a security cover that must be closed when a test is being done, otherwise the whole system should shut down for security reasons. In this figure can also be identified other important elements of a test bench such as the emergency button on the right which should be able to shut down the whole system in case of an emergency.

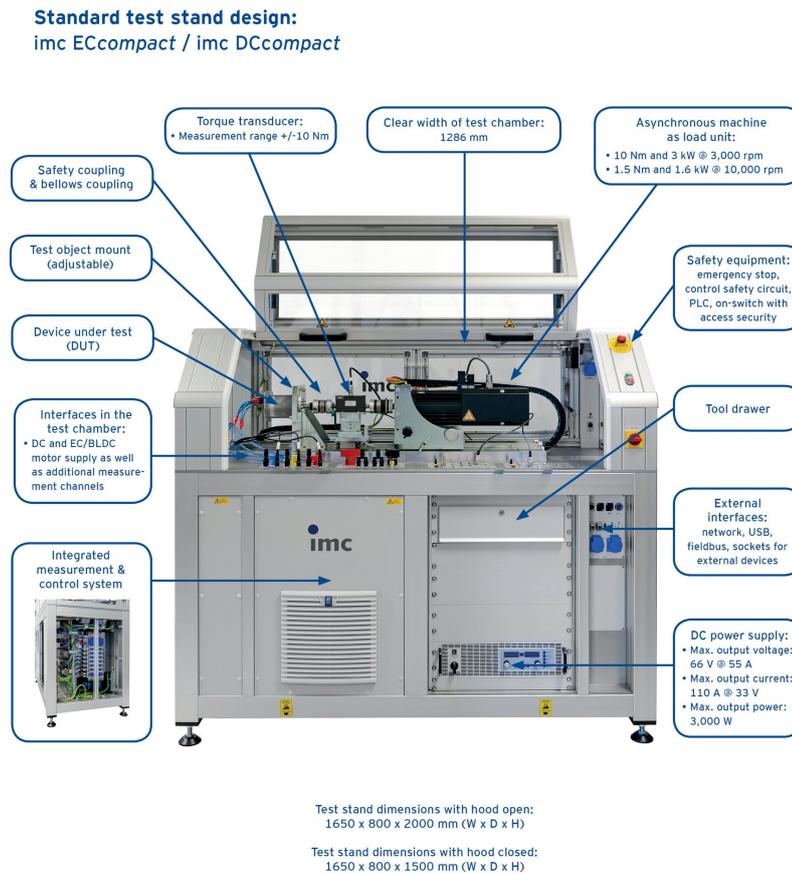


Figure 1.5: Complete Test Bench [7]

1.3 Functioning of a test stand

The functioning of test stand is quite simple and it follows a clear explainable power flow. The power flow of the system starts in the grid in alternating current which is then transformed into DC by a DC power supply. Through this DC bus we will supply power to both inverters, the inverter of the load machine and the DUT's inverter. To control both inverters there are two principal control modes which can be used indistinctly: in the first mode a reference torque is set to the load machine and a reference velocity for the DUT, the othe option would be to do it the opposite way. The most common mode is the first one but both would technically be possible. Operating our test bench like this we would allow to test our motor in every operational point that is desired by changing the references that are set to both inverters. For example: The DUT needs to be tested at 1000 rpm

and 20 Nm torque. Assuming there were no energy losses the load machine would be set to 20 Nm counter torque and DUT would be set to 1000rpm. The DUT would start rotating at the desired speed with a positive torque compensating the counter torque created by the load machine. For this exact case the power would flow first to the DUT then through the torque sensor which would acquire the torque and velocity in every time step and the energy would be consumed by the load machine (Dynamometer). This power flow can be explained in the Figure 1.6.

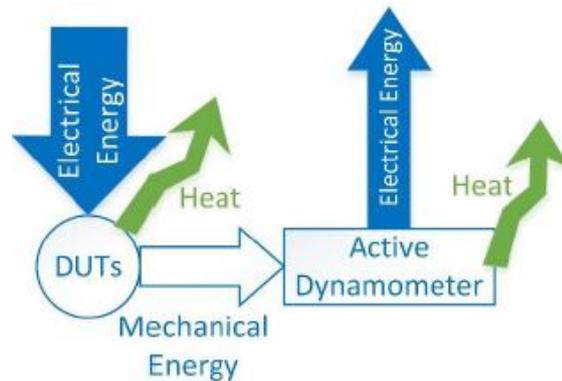


Figure 1.6: Power Flow [6]

1.4 Objectives

In this section the objectives of the thesis are going to be explained:

- Design a test stand with the lowest costs possible.
- The accuracy of the test stand must be kept as high as possible.
- The test stand must be safe for unprofessional use as it is going to be used by students.
- The test bench must accomplish the requirements given by the TUfast eco team, which will be given in the next chapter obtained.
- The test rig must be a portable test rig.
- The test rig must be compatible with the installation of a gear box.

One of the main objectives is to keep the precision of the test rig as high as possible without being too expensive. The reason being that the main function of this test bench is going to be measuring the efficiency of electric motors. Electric motors can have up to 95% efficiencies and a deviation of 1% in the precision of the test

rig could end in misleading measurements. Furthermore the costs of the test bench must be kept as low as possible, so one of the main challenges of this project is going to be to compare the different suppliers available and compare its prices and delivery times.

Chapter 2

Dimensioning of the test stand

This chapter deals with the dimensioning of the test stand. Firstly the mechanical requirements are going to be calculated from the data given by the team in order to limit the specifications of the test bench. Afterwards a selection and comparison of the most important mechanical elements is going to be explained. In this selection not only are the elements going to be selected but also they are going to be compared among all the different manufacturers that are available in the market. The selection is going to be explained in chronological order.

2.1 Mechanical requirements

In first instance the mechanical requirements to dimension the test stand must be calculated, so that the rest of the elements of the test rig are selected according to these. At the moment the Tufast eco team is using an electric motor (ILM 85x13 from TQ-Systems GmbH), whose specifications can be found in the annex at the end of the thesis. The ones needed for a first dimensioning are listed hereunder:

- **Max. Power** 440 W
- **Rated Torque** 1.44 N*m
- **Peak Torque** 4.66 N*m
- **Max. Speed** 7900 rpm

For the calculation of the mechanical requirements of the test stand, it is not only needed the specification of the actual motor but also the actual values that are used in the competition and the limits that are imposed in the competition by

the regulations of the Shell eco marathon. This is because in the competition the motor might not be used to its 100% capacity.

According to the data of the team a bigger torque than the peak torque of the actual motor will not be needed. Furthermore in the regulations of the competition state that the maximum allowed velocity is 40 Km/h. Knowing that the radius of the wheel is 275 mm and that the gear ratio is approximately 8 the mechanical requirements for the test bench can easily be calculated. As this test bench will need to be calculated for the use with a gear box and the gearbox is also important to calculate the mechanical output of the system with the gearbox to dimension the test bench.

Firstly the values without gear box are going to be obtained:

$$40 * 1.25 = 50 \frac{Km}{h} \quad (2.1)$$

$$4.66 - > \mathbf{5 \text{ N*m}} \quad (2.2)$$

$$\frac{50 \frac{Km}{h} * \frac{1000m}{Km} * \frac{1h}{3600s}}{0.275m} * 8 * \frac{60s}{2\pi} = 3858rpm \approx \mathbf{4000 \text{ rpm}} \quad (2.3)$$

Now the values with the gear box are going to be calculated:

$$4.66 - > \mathbf{5N * m} \quad (2.4)$$

$$8 * 5N * m = \mathbf{40 \text{ N*m}} \quad (2.5)$$

$$\frac{50 \frac{Km}{h} * \frac{1000m}{Km} * \frac{1h}{3600s}}{0.275m} * \frac{60s}{2\pi} = 482rpm \approx \mathbf{500 \text{ rpm}} \quad (2.6)$$

As the efficiency of the gearbox is not known by the team an arbitrary safety factor has been applied to the torque requirement, taking into account that already the 4.66 N*m peak torque of the motor was overdimensioned according to the data given by the team. Knowing that, from these two configurations (with and without the gearbox), the mechanical requirements for the load machine can be obtained. There are three possible solutions attending to the results previously calculated:

1. Dimension the load machine attending to the values without the gearbox from Equation 2.2, and Equation 2.3. Whenever a test with the gear box is needed, then another gear box with the opposite ratio will be needed to be attached to the load machine.

2. Dimension the load machine attending to the values obtained with the gearbox from Equation 2.5, and Equation 2.6. Whenever a test without the gearbox is needed, then once more another gearbox will be needed in the load machine side.
3. The final option would be to dimension the load machine attending to Equation 2.3 and Equation 2.5. In these case no gearbox would be needed for the load machine in any situation. But for this solution the price of the load machine could be higher.

For this project and to make it as simple and easy to use for the student, the design was elaborated according to the third option. Even though the motor might be more expensive the design of a gearbox for the load machine is not going to be needed, which would be a long and difficult work that might increase unnecessarily the complexity of the system. Not only that but also the attachment of another element to the system could also affect to the precision of this test stand. Further more we would keep the ease of use of the test stand as with this design option, only the half of the DUT would need to be changed for each test. The other half of the load machine would be fixed for every test regardless of the type of test and the test motor that is desired to be analyzed. This way we make a more user-friendly system that does not need much work on its setting up and is suitable for student ambient use.

2.2 Selection of principal elements

This subsection deals with the selection of the main elements that are going to be placed on the test stand. The 3 most important elements are going to be analyzed and compared with the different solutions in the market.

2.2.1 Dynamometer

The most important part of a test stand is its dynamometer. As explained before in subsection 1.2.1, the function of the dynamometer is to act like a braking system for the DUT in normal test stands. Dynamometers can be classified into two types: passive dynamometers and active dynamometers.

The first ones can only be used in tests where only testing the DUT in the motor mode is needed, this would be the case for a combustion engines. This means that the power flow comes from the DUT into the dynamometer and that the only function of the dynamometer is to dissipate the mechanical energy from the DUT in form of heat to brake the motor.

For the second type an electric motor is used as dynamometer, also called load machine. In this case the mechanical energy that comes from the DUT is transferred into electrical energy through our load machine which is being operated in generator mode by rotating and applying a torque in opposite directions. Consequently the energy losses in form of heat are minimized as they are transformed into electrical energy. But that is not the main propose of this configuration specially for this project as it is only thought for low power electrical engines. This means that the energy savings are not going to be meaningful. But for the objective of this project having an electric motor as a load machine would allow the test bench to test the DUT in all four quadrants of an electric motor (Figure 2.1). This is really helpful because as the competition consists in energy efficiency and saving energy, it is really important to test the generation performance of the motor.

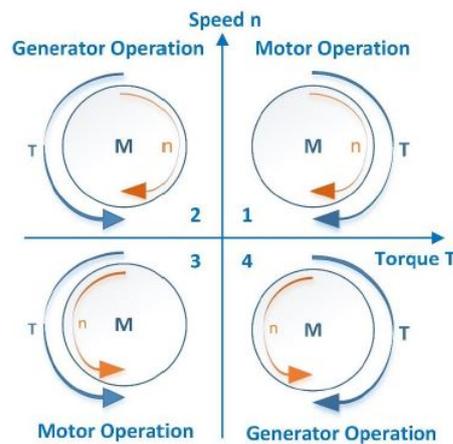


Figure 2.1: Four quadrant diagram [8]

Another extra advantage of the active dynamometers is that as the energy is not transformed into heat but into electricity the need for a cooling system in the loadmachine is not that critical. This makes the total system simpler and also probably cheaper as no air liquid cooling system is needed. This would bring extra costs for the water pump and deposit for the case of liquid cooling and in the case of the air cooling system the fans are not needed.

Taking into account all of this information, for the propose of this project an electric motor has been chosen as the best solution for the load machine for the test stand. After the type of dynamometer has been decided, the next step would be to decide which electrical motor technology would suit the best for the propose of this project. In the following Table 2.1, a comparison between the most important electric motor technologies can be observed.

Table 2.1: Electric motors technology comparison [6]

	Advantages	Disadvantages
BDC	<ul style="list-style-type: none"> - Speed control over a wide range - High starting torque - Constant torque in low speed range - High dynamic - Free from harmonics and reactive power 	<ul style="list-style-type: none"> - High maintenance cost due to commutator and brushes - Danger in explosive and hazard conditions due to sparking at brush - Normally lower max. speed - Low reliability - Low overloading capability - Low heat dissipation
BLDC	<ul style="list-style-type: none"> - Low maintenance cost - High efficiency - Higher speed range - High power density and torque to inertia ratio - Good heat dissipation - Synchronous drives with trapezoidal waveform 	<ul style="list-style-type: none"> - More complex with addition feedback and lower reliability - Expensive - Torque ripple - Danger of demagnetization of the magnets
PMSM	<ul style="list-style-type: none"> - High efficiency - Smooth torque possible - High torque/volume - High dynamic - Good heat dissipation - Synchronous drives with sinusoidal waveform 	<ul style="list-style-type: none"> - Expensive - Danger of demagnetization of the magnets
IM	<ul style="list-style-type: none"> - Low price and simple construction - Durable - Excellent dynamics with proper control - High speed operation possible 	<ul style="list-style-type: none"> - High complexity of rotor flux estimation - Complicated control - Lagging power factor - Lower efficiency - Lower dynamic

Attending to this table, many conclusions can be extracted. Even though their mechanical characteristics are great, the first type of motor brushed DC motor is not suitable for this project mainly because of the high costs that this motor would incur. The maintenance costs and the implementation of a cooling system for the load machine would exceed the budget. Furthermore as this test stand is thought for student use the least maintenance of the test stand is desired.

In relation with the brushless DC motor, they are expensive even though the maintenance costs of the BDC motor are eliminated. Furthermore its torque ripple would also affect the accuracy of the test stand. Therefore this motor technology does not fit the requirements for this project.

Permanent magnet synchronous motors have excellent characteristics and only one disadvantage. The only thing that must be kept in mind is the demagnetization of the magnets but this would not be a problem for the propose of this project because the test rig would be used in a magnetic safe ambient. However these motors can be really expensive but they are going to be considered for this project in case there is a market opportunity.

Lastly the Induction motors are motors stand out for their robustness. This characteristic fits perfectly the needs for this project as it is going to be used by students. Furthermore being robust would mean that this motor would incur less maintenance costs. The disadvantages shown in the Table 2.1 for this type of motor are not that important for the objective of this project, because a high efficiency is not needed and the complexity for its control can be easily solved with a good software development.

One further aspect that mus be taken into account is the maximum voltage that the motor can have, so that it is safe for student use without any protection. According to german regulation of low voltage DIN VDE 0100-410 414.4.5, "Ein Basisschutz ist im Allgemeinen nicht notwendig bei normalen, trockenen Umgebungsbedingungen für: SELV-Stromkreise, deren Nennspannung AC 25 V oder DC 60 V nicht überschreitet" [9]. So the limit voltage supply for the complete system inverter and motor should be under 60 Vdc so that it can be safe for student use without any special protection. Not only that but making the maximum voltage under the values specified by the VDE would reduce the total protection costs of the test stand.

Attending to the mechanical requirements calculated in section 2.1, the torque needed for the loadmachine was 40 N*m and the velocity 4000 rpm. In the Table 2.2 there is a list of different electric motors candidates that could fit the requirements previously mentioned:

Table 2.2: Motor comparison

Model	Technology	Pn (kW)	Vn (dc)	Tmax (Nm)	Nmax (rpm)	m (Kg)	Cooling	Price (€)
ATS 071-M1	PMSM	14,28	415	42,4	10000	27,8	Air	x
ATS 100-K0	PMSM	14,13	415	55,2	10000	34,6	Air	x
Mahle 14kW	PMSM	6	24-80	40	9000	11,3	Air	x
Mahle 15kW	IM	12	32-63	70	5000	36	Air	1800
Mahle 18kW	PMSM	7-13	24-80	60	9000	20	Air	Not available
Mahle 18kW	IM	4-8	24-80	90	8000	36	Air	2500
Mahle 20kW	PMSM	13	40-56	60	21000	22,9	Liquid	x
Linde EDM 112 LL1 50	IM	10	48	55	6000	34,1	Air	No Answer
Linde EDM 112 LL 150	IM	8,5	48	60	6000	34	Air	No Answer

All motors from this table offered an inverter from the same manufacturer which were compatible with their respective motors. This was as well another requirement as this might be helpful in the future in case some technical support is needed from the company.

The first two motors from ATS based on the mechanical requirements would fit perfectly but the DC voltage supply is higher than stipulated in the VDE regulation [9] to be used without protection. Nevertheless they were also included in the list to compare them as they were the ones that were already available in the team.

Another option would be the Mahle motors. From these motors the 20 kW Mahle motor was discarded because a liquid cooling would need maintenance, which would incur higher costs and make it more complex for student use. In order to keep it simple and easy to use for the student use, the other options were considered. The 14 kW motor was as well discarded because even though it fulfilled all the requirements the max torque was just the amount needed for the project. As it was specified as the max torque, presumably it would not be able to handle a test at 40 N*m for long periods of time and this could limit the possibility of doing future tests with higher torques. Then from the rest of the Mahle motors the most interesting one would be the Mahle 18 kW (PMSM). It satisfied all the mechanical requirements too a high degree and its weight was considerably low. But after asking to the manufacture the motor was not available. From the two left the decision was done attending to its price, as both fitted perfectly the requirements there was no need to spend more for more power. In summary the Mahle 15 kW motor is the most suitable for the propose of this project. In the Figure 2.2 there is a picture of the selected motor.



Figure 2.2: Mahle 15 kW motor

Finally two Linde motors were added into the table, because they also fulfilled the

requirements and in case they were cheaper, they would have been a better option. Unfortunately no quote was given from the company.

2.2.2 Torque Sensor

One of the most important elements in a test bench is its torque sensor. This element is responsible for measuring the torque and sometimes as well the velocity of the shaft. From these measurements most of the conclusions of the test that is undergone in the test stand are extracted. There are many possible options to measure the torque that is applied in the shaft. One solution and the cheapest would be to use a load cell to measure the force applied by the DUT. In the Figure 2.3, there is an example of how this system would look like.



Figure 2.3: Load Cell type solution

As it can be seen in this test stand there is no torque sensor in between of the load machine and the DUT. Instead there is a load cell which is marked in red in the Figure 2.3. In this system the DUT is suspending and there is a stick which is attached to the case of the motor. The way to calculate the torque in this system would be to multiply the force measured by the load cell by the length of the stick. This solution would be a very cheap solution but the precision of the measurement would not be that accurate as there is an uncertainty in the length of the stick which would be added up to the tolerance of the load cell. Attending to the necessities of this project a higher accuracy is demanded. As the main

objective of this test stand is to measure the efficiency of electric motors to be able to compare them, there is a big need for a high precision sensor. Most electric motors have an efficiency of more than 90%, a small error in the measurement can end in misleading values.

The other option is the torque transducer and there are many types attending on how much precision is demanded, and the maximum torque that the sensor must withstand. Mainly there are two types: shaft sensors and flange sensors. The first ones are suitable for low torques starting from 0.5 N*m and they are cheap. On the other hand the flange torque sensors are capable of measuring torques up to MN*m and they have got really high precision but they are considerably more expensive. Whereas the first ones cost around 2500€ the flange sensors can cost up to 15000€. Considering that this project is also looking to keep the costs as low as possible and that the maximum torque measurement needed is relatively low the best option would be the shaft sensor.



Figure 2.4: Left: Shaft sensor — Right: Flange sensor

The market leader in this sector is HBM and at the moment they are offering two models of this type: the T22 and the T21WN. Attending to the design option that we selected in section 2.1, the design values of the torque sensor are 40 N*m and 4000rpm. In the Table 2.3, there is a comparison of the two torque sensors.

Table 2.3: Torque sensor comparison

Model	Mnom (N*m)	Rotational nominal Speed (rpm)	Lateral limit force (N)	Output	Output at 0	Error	Frecuency output	Price (€)
T21WN	50	13.500	88	-10 — 10V 5 — 15kHz	0±0.05 V 10.000±50 Hz	0.1%	yes	3800
T22	50	12.000	210	-5 — 5V 2 — 18mA	0±0.2V 10±0.2mA	0.3%	no	2000

From this comparison there are some conclusions to be extracted. Both of the sensors fit our mechanical requirements of torque an velocity. One advantage of

the T22 is that it has got a higher lateral limit force, as it is going to be for student use, the misalignments might be a little bit higher therefore the fact that it has a bigger lateral limit force is an advantage. Regarding its precision the T21WN has got a little bit more precision 0,1% in comparison with 0,3%, which is not that big difference. But the T21WN has got the option of a frequency output which is more trustworthy than an intensity or voltage output. Furthermore the ranges of the T21WN are much higher than the ones from the T22 which indicates a higher resolution. Nevertheless the price for this sensor is much higher than the T22 and the difference between the two is not that big. Therefore the T22 sensor suit better the requirements of this project in terms of the budget and still with a considerably high precision.

Lastly before every operation a calibration process must be done in order to eliminate the zero output error that the torque sensor might have.



Figure 2.5: T22 torque sensor

2.2.3 Couplings

As explained previously in subsection 1.2.1, the couplings have several functions:

- Transmit the mechanical energy from one shaft to the next one with the least energy loss possible.
- Limitation or interruption of the maximum permissible torque to protect the components.
- Damping of vibrations between the individual machines.
- In some cases electrical insulation.

- Compensation of shaft misalignment (axial, radial and angular) with low restoring forces.

Shaft misalignment is due to its assembly or its fabrication tolerances and causes an unnecessarily high static load on the shaft bearing when two components are rigidly connected. In many cases, precise alignment of components alone would not be sufficient to keep these loads away from the bearing points, since the dynamic and static machine condition differs from elastic deformation of the frame or from thermal influences.

There are mainly three types of couplings according to their elastic behaviour:

- **Torsionally rigid couplings:** are designed to be torsionally rigid in the circumferential direction and flexible in the axial and radial directions. Angle of rotation and torque are passed through the clutch without phase shift. The shaft misalignment is compensated by the design of the coupling. Figure 2.6a.
- **Torsionally flexible couplings:** have spring bodies that are mostly made of elastomer materials. The torsional spring stiffness and damping that are advantageous for the application can be achieved by designing the elastomer appropriately with a suitable Shore hardness and shape. With these couplings, the shaft misalignment is compensated by the deformation of the spring body. Figure 2.6b.
- **Highly flexible couplings:** are characterized by a large-volume (elastomer) spring body that enables large spring deflections. In general, these elastomeric bodies are endowed with low rigidity. Both the torque and the angle of rotation are conducted through the clutch with a clear phase shift. These properties also compensate for a strong shaft misalignment. Figure 2.6c.

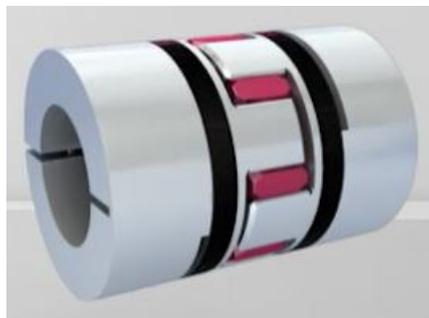
For this test stand construction, the rigid couplings are going to be used. It is important that the couplings for this test stand are rigid in the torsional direction, otherwise the measurements of the torque sensor could be affected. For the election of the coupling in this project, the couplings offered by the torque sensor supplier were selected. This way the perfect functioning of the system would be guaranteed, additionally the delivery time was shorter. The price for this piece in this case was around the 600€ for each piece.

Although there would be needed three couplings for this project, because of the compatibility of the gearbox, only two were ordered. One that is fixed only once for the load machine and the other one for the output of the gearbox. If needed in the future an adapter piece for the shaft of the motor would be required when a motor test is to be done. This way we limit the times that the coupling is installed

and uninstalled and the price of a third piece is avoided.



(a) Rigid Coupling



(b) Flexible coupling



(c) Highly flexible coupling

Figure 2.6: Coupling types

For the coupling that connects the shaft of the load machine to the torque sensor the diameters were 24 mm and 28 mm which are the sizes of the torque sensor shaft and the load machine shaft respectively. The shaft of the load machine has got a spline on it but no adapter for the shaft was selected as it would mean an extra centering error that could bring misalignments, furthermore as stated in the friction force formula the friction does not depend on the surface so the actual fit of the coupling should be enough to transmit the torque. On the other side as it is going to be a coupling used for various purposes gearboxes, and different motors a relatively high diameter was selected for the DUT side of the coupling. The manufacturer offered a standard coupling that was offered directly with 24/24mm sizes, so this was selected for the DUT side as it was cheaper and the delivery times were shorter.

2.3 Test stand design

In this section is going to be explained what type of configuration was selected for this test bench.

For the design of the test stand, it was decided that it was going to be placed on top of a T-slot plate. Placing it on top of such plate would allow the system to be calibrated and aligned easily in the axial direction. Furthermore it would provide the test bench with the flexibility for future alternative configurations. The test stand is going to be structured with the previously mentioned elements as shown in the Figure 2.7. This figure shows the actual look of the test bench when a test is assembled with the gear box, as it is the most complex configuration. From left to right this is how the elements will be mounted. Firstly the load machine is attached to an angle bracket, then a coupling joins the shaft from the torque sensor and the load machine, then comes the torque sensor which is attached on the other side to the adapter piece of the gearbox by a coupling. These couplings will try to compensate the actual errors due to the tolerances in the fabrication process and assembly. Then comes the actual gear box itself whose bearings are resting on a platform. At the end on the right the testing motor is held as well by another bracket but in this case as the testing motor is going to be changed often an adapter plate has been used as an interface.

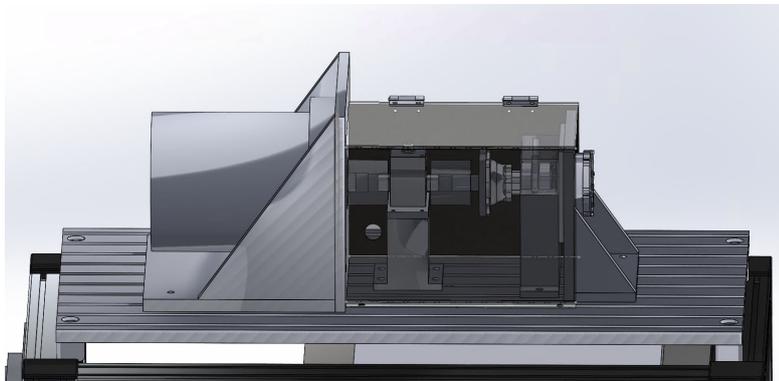


Figure 2.7: Test bench

Chapter 3

Elaboration of mechanical design

In this chapter the design process of the complete test stand is going to be discussed. Once all the different main mechanical elements of the test stand have been previously selected in the chapter 2, the size of the test bench can be calculated and also its structure can be designed. The style of the final version of the test stand is similar to the one shown in the Figure 1.5. But for the propose of this project the test stand will be mounted with rollers so that it can be portable and transportable from one room to another.

All the self designed parts are going to be manufactures in the workshop of the chair, furthermore all their technical drawings for its constructions are attach to this document in the annex.

3.1 Trolley Design

For the design of the trolley, the width is limited by the width of an standard door. Attending the DIN norm 18101 [10], the standard free way of the smallest doors are the following: 591, 716 and 841mm. The first ones are increasingly out of use, so the limit for the width of the trolley will be set in 716 mm. Regarding the height, it is important that the test stand is going to be designed taking into account the ergonomics for light work. The ideal height for a standing working desk depends on the height of the person and the type of work which is going to be done on the desk. The height for a standing desk of a watchmaker is going to be higher as usual, because a higher precision is required. There are many studies about ergonomics but mostly the ideal height ranges between 80 cm and 120 cm. In the Figure 3.1 there is one example of one of the multiple ergonomics studies. For this project the objective height is going to be an intermediate height, around

100 cm.

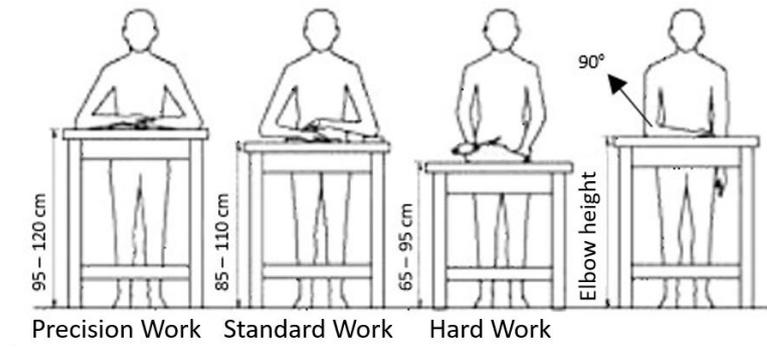


Figure 3.1: Ergonomic study about table height

For the special propose of this test stand for low power electric motors, a mobile framework with a T-slot plate on top was selected as the design, see Figure 3.2. On top of the T-slot plate are place every element of the actual test stand. As said before the fact that a T-slot plate is being used as the base of the test stand allows a longitudinal alignment for all the elements that are required to be placed on the test bench. These T-slot plates are standardised in length and width: knowing that the smallest doors are 716 mm and that the biggest element in the whole system is the loadmachine (250mm wide), a T-slot plate of 500x1000 mm in size will fulfill the necessities for this project. For the framework the size is going to be as long as the T-slot plate but the width is going to be slightly bigger 600mm, this still fulfills the maximum width fix by a standard door.

Under the framework of the trolley are the wheels placed. The castors that are to be installed must be steerable in order to be able to transport the test stand freely through all the corridors and doors. Furthermore all the four castors must have a braking system in order to avoid the rolling away of the whole system as a consequence of not dumped vibrations.

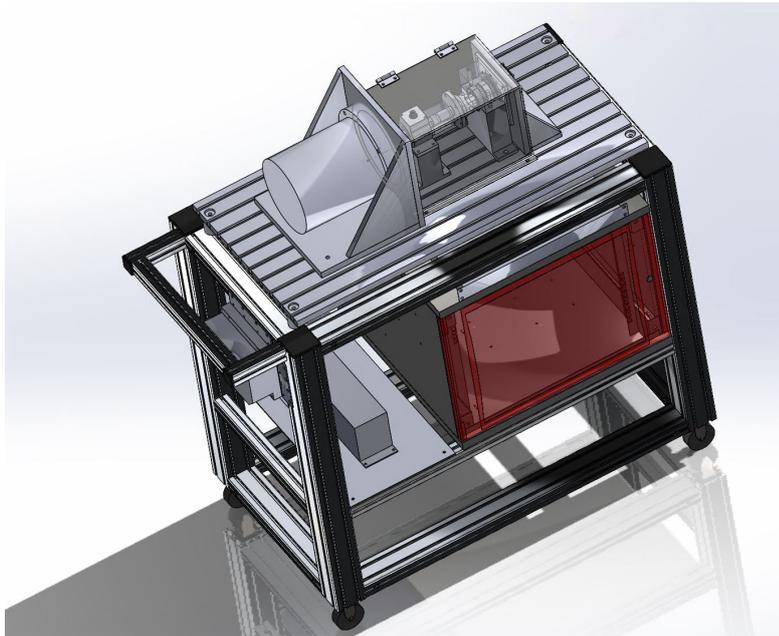


Figure 3.2: Test stand design

In this design there are 4 dampers on the corners of the T-Slot plate in order not to transmit the vibrations of the system to all the electric and the electronics that are housed inside the framework. This dampers must be soft dampers as the type of the vibration of the test stand is going to be a high frequency vibration.

In this framework all the load that comes from the weight of the elements of the test stand is going to be supported by the four pillars in the corners. This pillars are laying directly on the four castors which also have to be able to withstand the whole weight of the complete system.

There is also a middle ring that is meant to support all the electronics and electric elements that are necessary. The other function of this ring is to place all this elements in a more accessible height for the user. Some of these elements are: Inverter, DC Power supply, Braking resistance, relays, ...

3.2 Assembly parts of test stand

In this section almost all the assembly parts of the test bench are going to be explained. also in the annex of this document all the drawings of this parts can be found.

3.2.1 Load machine Bracket

For the mounting of the load machine a bracket system was selected as the best solution. Mainly due to the mounting points that were available on the motor, which were only placed on the vertical side and not on the bottom. This bracket is meant to hold the weight of the load machine and the motor is going to be screwed to it by four screws as it can be seen in the Figure 3.3. The connection to the T-slot plate is going to be done by four screws which are going to be screwed to the T-slots of the plate. To do this the bracket has got 4 through holes that have been sized to the biggest size according to DIN standards. This way the Y position of the bracket can be slightly adjusted so that the misalignment is not that big due to fabrication tolerances. This means that the losses in couplings will be lower. This is the cheapest and simplest method to adjust the whole system in the Y direction, which suits perfectly the objectives for this project.

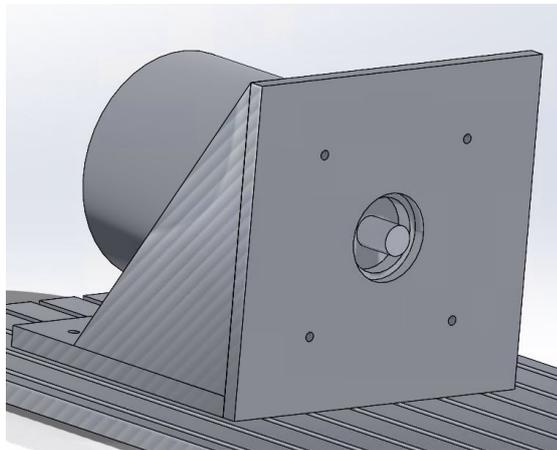


Figure 3.3: Load machine Bracket

For the design of this bracket the vertical and horizontal plate of the bracket must be as perpendicular as possible so that the shaft is parallel to the T-slot plate and the couplings have to compensate the least possible misalignment. The material selected for this part is steel due to the relatively high mechanical requirements of holding the motor which weights around 36 Kg. Among all the steels available the one with the best performance/price could be the S-355, which is the best suitable steel for our requirements and budget. Nevertheless this steel could suffer oxidation, therefore a varnishing of the part after its fabrication would be needed. For the rest of the parts that will be built in this type of steel in the test bench will need as well this varnishing.

In terms of the fabrication of the bracket as it can be seen in the Figure 3.4,

the bracket has been divided in sub-pieces. Piece number 2 where the motor is going to be screwed in, pieces number 2 and 3 which stiffen the bracket and the number 4 which is the base of the bracket. The reason for this solution, being that the machining of the complete part would be very costly in terms of the material needed and the fabrication process. The different subpieces are going to be laser cut from a raw material plate with a thickness of 15mm. Every subpiece of this part has got a thickness of 15mm in order to save material costs. Except for the subpiece 4 which is a bit thicker as it is going to strengthen the T-Slot plate, for this reason it is 20mm thick. To join the sub-pieces a welding process is going to be done as it is the most resistant method in order to keep the pieces together and withstand the weight of the motor.

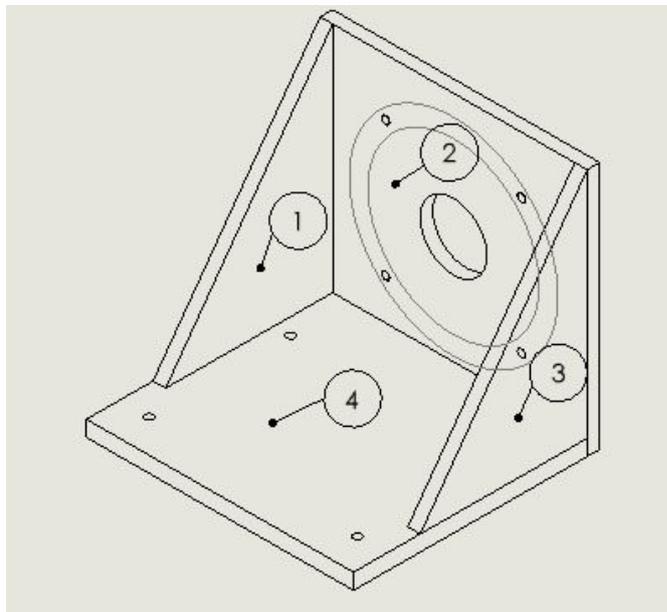


Figure 3.4: Subpieces Loadmachine Bracket

For the design of this part and the rest of the parts it was very important that the tolerance for the height of the mounting points and of the holes through which the shaft goes was really precise. The reason for this is that the couplings have to absorb the least misalignment possible. Nevertheless this system is also thought that if needed because of fabrication errors, very thin vacuum sheets of metal can be fitted underneath the parts to adjust the height. Also in the center part of the subpiece number 2 there is a centering hole to help the alignment of the whole system.

3.2.2 Torque Sensor Platform

The torque sensor platform consist on 2 parts as it can be seen on the Figure 3.5. The lower part is the platform itself and on top there is an interface plate which was needed because the only mounting points of the torque sensor were on the underside of the sensor. As the forces that these parts have to withstand are not that big, the material chosen for this part was aluminium which is lighter and does not require varnishing. The only function of the platform is that it keeps the torque sensor fixed to the T-slot plate so that it can measure accurately the torque in the shaft. For the connection of the platform to the T-slot plate also 4 through M8 holes were place to allow the adjustment of the platform in the Y position.

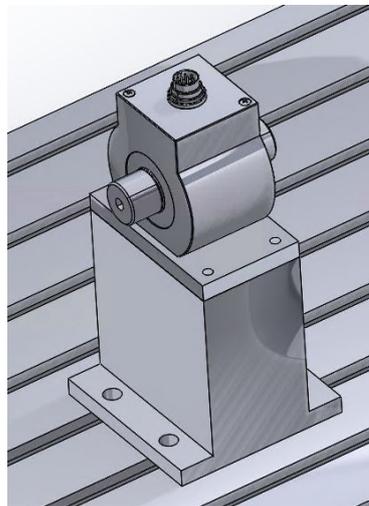


Figure 3.5: Torque Sensor Platform

As the torque sensor only could be mounted from the bottom an interface-plate was required. To join the torque sensor to the interface-plate four countersunk screws were used, as it can be seen in the Figure 3.6. This way the screws did not interfere in the assembly of this plate on the platform. The interface-plate is screwed by four screws from the top to the platform itself. And from the bottom of the adapter plate four countersunk screws are inserted and screwed into the sensor. So for the mounting of this part first the countersunk screws should be first mounted to the sensor an then the adapter plate should be screwed to the platform.

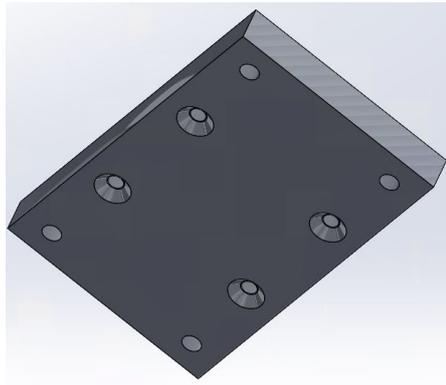
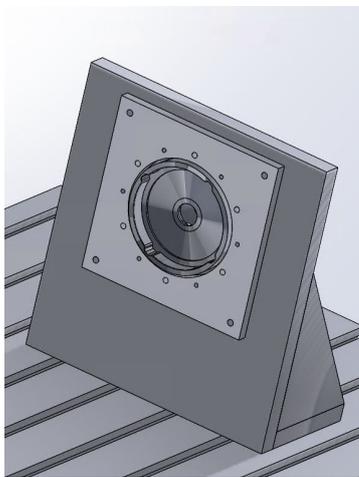


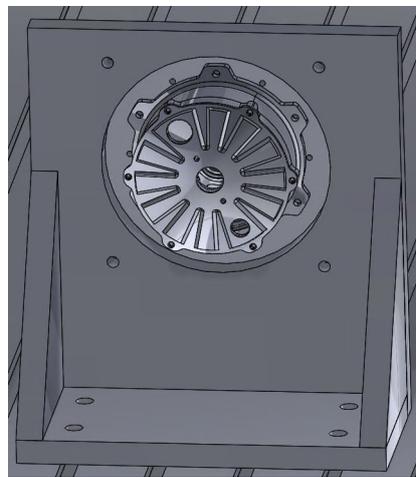
Figure 3.6: Bottom view of Interface-plate torque sensor

3.2.3 Test motor Interface-plate and Bracket

As in the case of the load machine the solution selected for the assembly of the test machine a bracket was designed. The difference in this case is that as the test machine is going to be replaced more often than the load machine, so an interface-plate has been added, so that in the case of the necessity of testing another motor, only the interface-plate would be needed to be changed. The Figure 3.7a shows how the complete system would look like.



(a) Rigid Coupling



(b) Flexible coupling

Figure 3.7: Test machine Bracket

As in the case of the load machine this bracket has also been divided into sub-parts because of the same reasons as in the load machine bracket. In the Figure

3.7b can be seen that all the sub-parts of the bracket are the same as in the load machine bracket. In this case even though the mechanical requirements to hold this motors are not going to be that demanding as for the load machine, the material selected was as well the S-355. As for the other bracket all subpieces here are 15mm including the base. They are going to be also laser cut and welded together. This bracket would need as well a varnishing so that the oxidation of the part is avoided.

In reference to the interface plate there are different function holes that are pointed in the Figure 3.8. The holes number 1 they are used to attach the interface to the bracket, they are positioned in the four corners of the plate. All future interface plates will need to be built with the same dimensions and positioning of these holes. The six equally spaced number 2 holes are through holes that will be used when a gearbox test needs to be done. In this case the motor case will be screwed directly into the gearbox holder as it will be explained after. The six last holes, number 3, they are meant for the case of the DUT test. In this case simply the motor is going to be screwed into the interface plate. This interface plate will need to be milled on both sides so that it is as flat as possible. This way the misalignment due to this part is reduced.

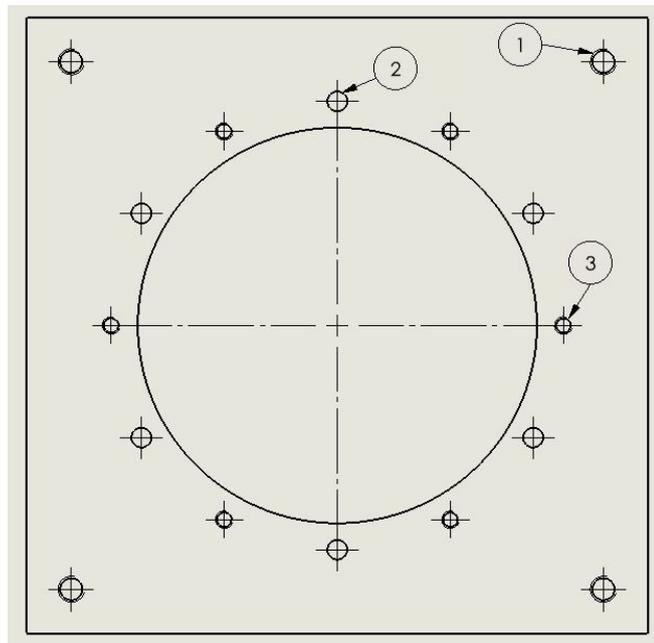


Figure 3.8: Interface Plate

3.2.4 Cover

The cover has mainly two functions: prevent from touching when a test is being undergone and a protection function in case a part is not well tighten and they fly off. This cover is covering all movable parts of the test stand, this means: torque sensor, both couplings, load machine shaft and gearbox. This can be seen in the Figure 3.9.

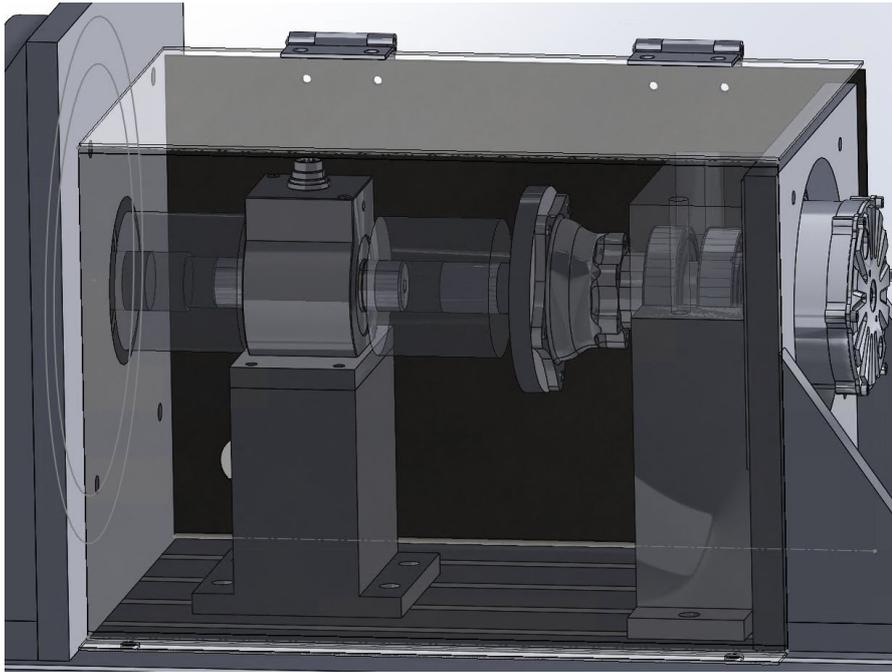


Figure 3.9: Cover

The cage consists in two parts the case and the cover. These two parts are two metal sheets that are going to be bent so that they can be screwed into the T-slot plate. This fabrication method is really cheap and for the function of this case it is perfectly well suited, as in the workshop of the chair the maximum bent thickness was 1.5mm this was chosen as the thickness for the manufacturing of this part. To open and close the cage these two plates are joined by two hinges on top that are going to be screwed with nuts on the other side. Additionally a sensor is going to be placed so that in case the case is opened when a test is being done that the wholes system shuts down. The material for this part is going to be steel with a coloured varnishing to indicate that this is a safety part and to avoid once more the oxidation of the part.

As this test bench is also thought for test without the gearbox the design of the case has been done so that the Test machine bracket can be slid through inside as

it can be seen in the Figure 3.9. In the case of the tests without the gear box the bracket will be simply needed to be slid deeper inside. Making the design this way we save the costs for two cases and no mounting and dismounting will be needed between tests by the user.

3.2.5 Gearbox holder

As it was said before in the introduction this test bench is also thought to be able to do gearbox tests. In the Figure 3.10 there is a picture of the actual gearbox that was used for the car of TUfast eco in the 2022 edition. This gearbox from the TUfast eco team is a planetary gearbox with a fixed ratio. The sun gear of the planetary is attached to shaft of the motor then the planets of the gearbox are joined to the wheelhub which goes directly to the wheel itself. In order to rest the wheelhub two bearings have also been mounted and that have been also given for the design of this test stand. One bearing is the fix bearing, in this case the one on the left of the Figure 3.10 and the other is a loose bearing so that there are not any internal forces in case of thermal dilatation due to high speeds.

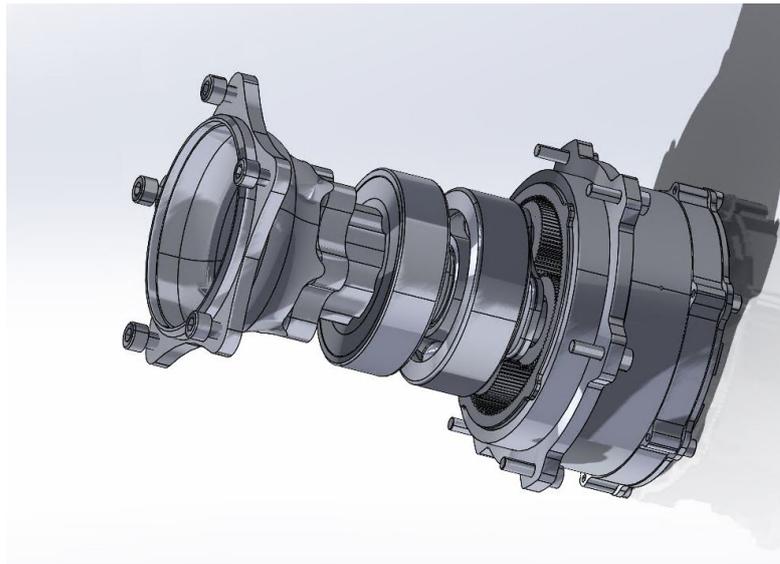


Figure 3.10: Gearbox

The solution to mount this gearbox in the test stand is a two pieces platform, see Figure 3.11. The reason for this type of solution is that it must be mounted and dismounted so that it can be once more installed back in the car. As it can be seen in the Figure both pieces are screwed together by two screws that are placed on the top. The bottom part of the holder is screwed to the T-slot plate as all

the rest of the parts mentioned before. For this part the material chosen was steel because of the thermal requirements due to the high speeds that the test motor is going to perform.

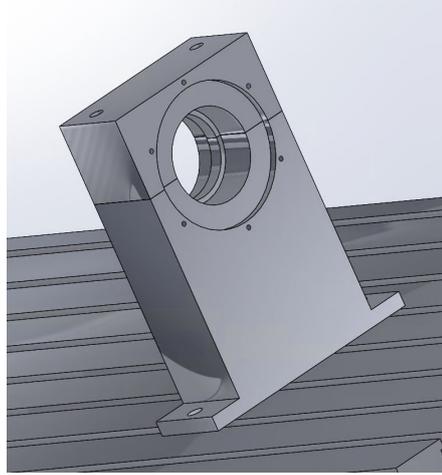


Figure 3.11: Gearbox Platform

There are four bores with different diameters that can be identified in Figure 3.11 with different functions. In the Figure 3.12 there is an inside view of the bearing holder. From left to right: the first one is for the fixed bearing so the fit for this bore is going to be the tightest, then comes a smaller bore in order to fix the position of this first bearing in the longitudinal direction, then comes the second bore for the loose bearing which is going to have a looser fit in order to free the dilatation due to the thermal losses that come from the high speeds and the last bore is a thin bore to house the planetary gearbox. This last bore also keeps the oiling of the planetary gearbox inside the system as this platform for the gearbox is also going to be screwed to the interface plate of the test motor so that there is no free space in between. These screws can be seen in the Figure 3.11 and Figure 3.8 indicated as holes number 3.

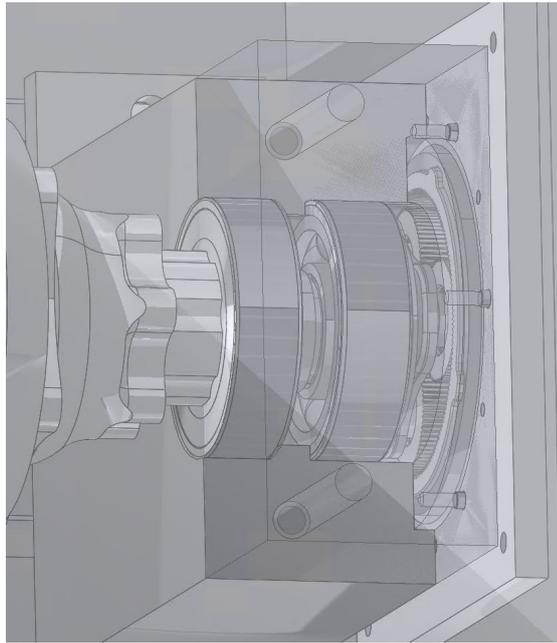


Figure 3.12: Gearbox Platform Inside View

3.2.6 Wheelhub Flange

As seen in the previous section in the Figure 3.10, the output of the gearbox ends in a wheelhub which is meant to be connected directly to the wheel of the car itself. In order to adapt this piece to the torque sensor this piece was designed, see Figure 3.13.

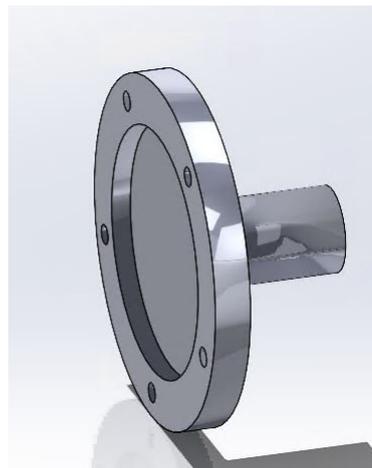


Figure 3.13: Wheelhub Flange

This part is connected to the wheelhub by five M5 screws that are going to be screwed into the wheelhub itself. So the flange has got five M5 through holes for the screws equally spaced. Also there is a centering hole that fits the actual rim of the wheelhub, the fit selected for the centering of the piece was a slight clearance fit. For the diameter of the shaft it was selected according to the inner diameter of the coupling and with the fit that was suggested by the manufacturer in this case 24mm g6. This part was made out of aluminium so that the moment of inertia of the part was as low as possible. The outer diameter of the whole piece was selected as 98 mm so that the raw material which comes in sizes of 100mm could be machined.

3.2.7 Inverter system

For the inverter as it is stated in the data sheet, a heat sink was needed to cool down the inverter in case the maximum power is required. Furthermore it was specified that in case the inverter was going to be mounted in a still air environment it is recommended to mount it in a vertical position. The cheapest and simplest way to do so was hanging the inverter from the frame of the trolley as it can be seen in the Figure 3.14.

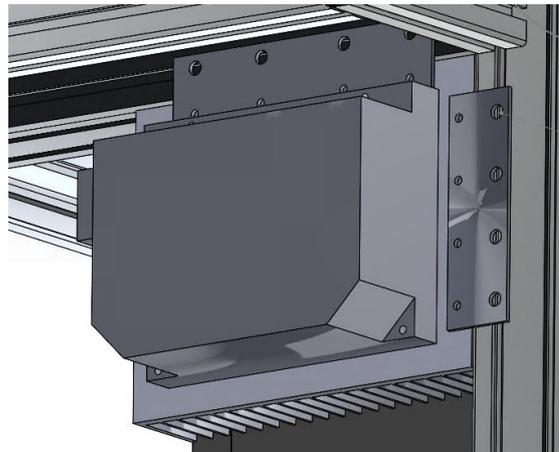


Figure 3.14: Inverter Assembly

In this inverter assembly a thermal paste is going to be applied in between the heat sink and the inverter so that the cooling is more efficient. The heat sink is going to be screwed to the heat sink by the four assembly screws that are given by the inverter itself. Then the heat sink is going to be mounted to the framework of the trolley through 2 thin plates in order to fix it in both directions.

Chapter 4

Detail of the design

In this chapter all the missing parts and the different parts that were presented in the previous chapter will be explained in more detail.

4.1 T-slot plate

To choose the T-slot plate a market research was undergone and the following options were found. In the Table 4.1 a comparison of the available options can be seen.

Table 4.1: T-slot plates Comparison

	Brand	Comments	Price (€)
1	isel Germany AG	Only M6 / Aluminium and 250x1000	400
2	Vacuum table UK	Aluminium	1146
3	Maschinen Werkzeuge	Steel	1585
4	Vakuumtisch	Steel	1579
5	Vakuumtisch	Aluminium	1331
6	Tnutenplatte	Steel and Alu / Nach Anfrage	?

Mainly there are two possible materials for T-slot plates in the market, either steel or aluminium. Aluminium is a slightly cheaper material and much lighter and steel but it is not as stiff as steel. Among all the options in this table the first option from Isel Germany has a really affordable price even though it was made in aluminium but after asking them, they could only build T-slot plates with a maximum width of 250mm. As the load machine alone itself it was already as big

as the T-slot plate this option was discarded. The second option was the second most interesting but the problem of being outside the EU and possible extra costs for importing this piece, it was also discarded. Among the rest of the options, the price difference between being aluminium or steel was not that big, therefore the fourth option of the steel plate was selected for the project. With a T-slot plate made of steel it is guaranteed that it will withstand all the weight of the parts that are going to be mounted on top.

In the Figure 4.1 there is a picture of the actual T-slot plate that was selected for the project. In the four corners there are four M8 through holes that are going to connect with the soft dampers, which are meant to eliminate the vibrations. These through holes are inside countersinkings so that whatever may be placed on top can be slid over. The countersinkings have been designed according the DIN 974-2.

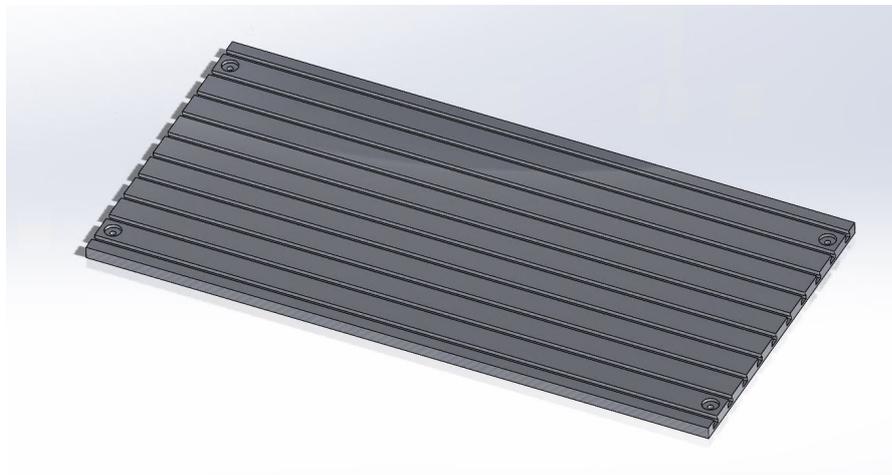


Figure 4.1: T-slot Plate

The actual dimensions for this T-slot plate are the following: 1000mm long, 500mm width and 20mm thick. This makes an actual weight for this T-slot plate of around the 78Kg according to what the manufacturer states on their web page. The T-slots are made according to the DIN 508 norm and with a separation between the slots of 50mm. These T-slots are prepared for T-nuts of M6 and M8 sizes, nevertheless all the parts designed in this project have been dimensions with M8 screws so that the number of screws needed was smaller. This way the size of the parts designed is going to be smaller and therefore cheaper.

For the assembly of the parts in the T-slot plate the actual width of the T-slots is slightly bit bigger tan 8mm, being 10mm. These extra 2mm can be used to adjust in the Y direction the parts so that they are completely aligned.

4.2 Dampers

The use of a test bench usually creates vibrations due to the high speeds that can be achieved by an electric motor. These vibrations most of the times are high frequency vibrations and to eliminate these vibrations in the framework there are four rubber-metal dampers. There are 3 types of rubber-metal dampers: on both sides with a screw, on both sides with a threaded hole or one side threaded and the other with screw. For the installation of these dampers the last were chosen. The screw part is going to be screwed into the t-nut of the framework and the other part is going to be facing the T-slot plate. The size of these dampers was 40mm diameter, 40mm height and M8 threads. As stated by the manufacturer the maximum weight for the damper is of 120Kg each, knowing that the weight of the most heavy elements is 80Kg of the T-slot plate and 70Kg of the load machine plus its bracket, the dampers are able to handle that total weight.

4.3 Framework of the Trolley

The framework is made out of aluminium profiles of the Maytec brand, nevertheless most of the aluminium profiles offered in the market are interchangeable. There are different sizes of beams but in the construction of this test bench the following sizes were used: 40x40, 40x80 and 80x80. All these beams have slots to fit into them the necessary M8 T-nuts.

The main structure of the framework consists on a cube made out of 12 beams as it can be seen in the Figure 4.2. These 12 beams consists of 2 rings the upper ring and the under ring plus the 4 columns. Both rings consist on 4 beams of the 40x80 size. The four columns of the 80x80 size which are going to transmit all the weight of the actual test stand to the four wheels underneath. These wheels that were selected from the Maytec catalogue are capable of holding 80 kg each, this makes a total amount of 320 Kg. This makes a total size of the framework including the wheels of 975mm height, 600mm wide and 1200mm long (including handle) aproximately.

Regarding the weight in the following Equation 4.1 the weight capacity of the test bench is going to be calculated. According to the datasheet given by the suppliers the weights of the bigger elements are the following: 80kg T-slotplate, 36Kg framework, 36Kg loadmachine, 30Kg the load machine bracket, the other bracket 7Kg and the Rittal flatbox for the electronics is 27Kg.

$$80 * 4 - 80 - 36 - 36 - 30 - 7 - 27 = 104Kg \quad (4.1)$$

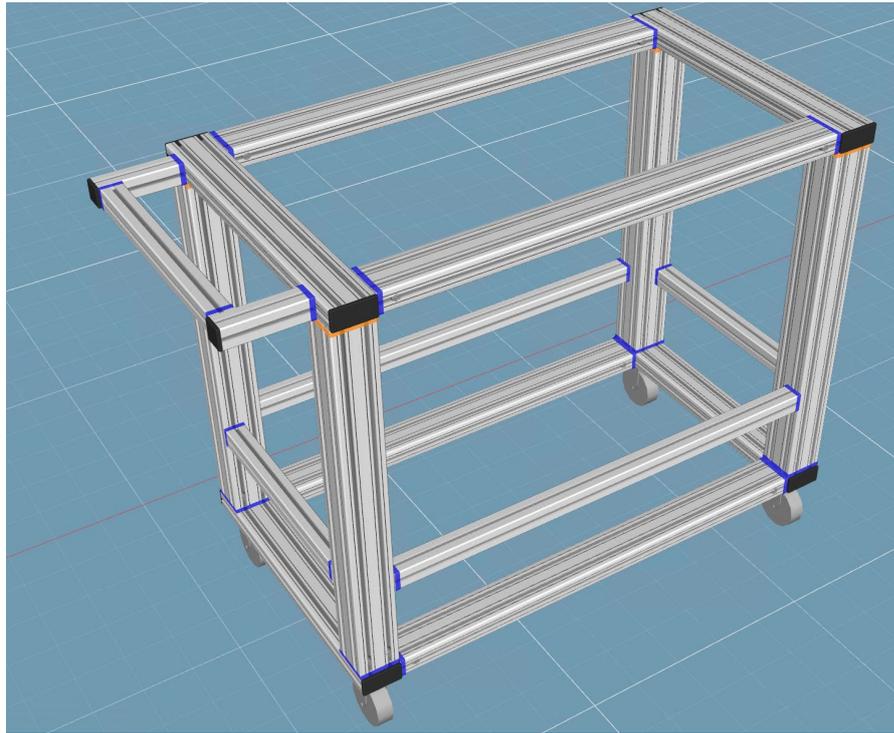


Figure 4.2: Framework of the Trolley

This leaves a free weight to work with of around 104 Kg extra Kilos that can be loaded on top of the test stand. The next option offered in the catalogue for the wheels could only bear 55Kg each, this would mean that the capacity of the test stand would already be to its maximum only with the elements mentioned above.

On the left part of the framework, a handle was installed out of 3 beams of the 40x40 size, see Figure 4.3. This handle has two functions: The first one being obvious is to be able to push the trolley comfortably in order to transport it and the second one is to protect the inverter which is going to be built on this side of the framework. As it was previously shown in the Figure 3.14. This way it is avoided an accidental collision of the user with the inverter.

On the frame work there is also a middle ring as it can be seen in the Figure 4.2. The function of this middle ring is to put all the electronic elements in a more accessible height for the user. The size of these beams is as well 40x40 as they do not have to withstand much weight.

The whole frame work is connected with universal connectors that are installed as shown in the Figure 4.4. This is just for the case of the Maytec beams but there are other available options in the market that are mostly interchangeable.

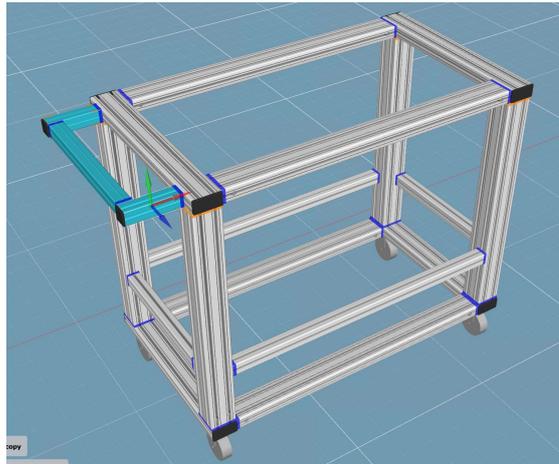


Figure 4.3: Handle of the Trolley

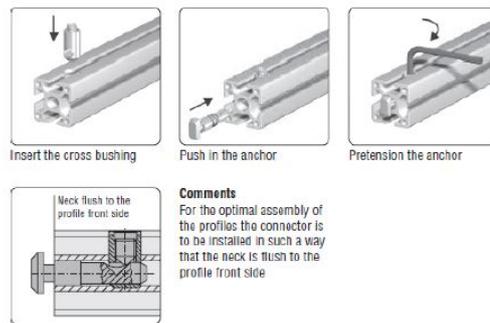


Figure 4.4: Framework Universal Connector

4.4 Electrical enclosure

To house all the electronics of the test bench an IT enclosure of the company Rittal was selected. The dimensions of this box are 600 x 492 x 600 mm with 9 height units to install the electrical components. As it can be seen in the Figure 4.5, the box has been placed on top of the middle ring of the framework. The reason for these as it was explained before is that all these electrical components are more accessible to the user.



Figure 4.5: Rittal Enclosure

To fix the IT enclosure once more the T-nuts of the framework are going to be used. To do so the box will need to be drilled in were the T-slots are positioned, a total of eight holes will be needed. Two holes on the bottom front part of the box, two at bottom back part and likewise 2 at the right part back and front of the box.

For the installation of the DC supply which on the Figure 4.5 is positioned on top of the IT enclosure, at an accessible height for the user there are 2 possible assembly options. The first one would be just to place it on top of the box without any need for drilling and joining it to the box as on the bottom of the DC supply there are already 4 rubber pads so that it does not slide through any surface. Nevertheless if needed, due to the undamped vibrations, at the front of the DC power supply there are 4 mounting points at the right and left. These would be used with a joining thin plate that would be screwed to the DC power supply itself with some nuts and to the Rittal box. However the box would be needed to be drilled twice more.

4.5 Inverter Heat Sink

For the cooling of the inverter as said before in the subsection 3.2.7 a heat sink is required. The manufacturer of the inverter did not suggest neither offer any heat sinks so the one chosen for this project was an standard heat sink designed for another inverter with similar specification as the one selected for the project. As it is not suited exactly for the one in this project some modifications had to be

done as it can be seen in the Figure 4.6.

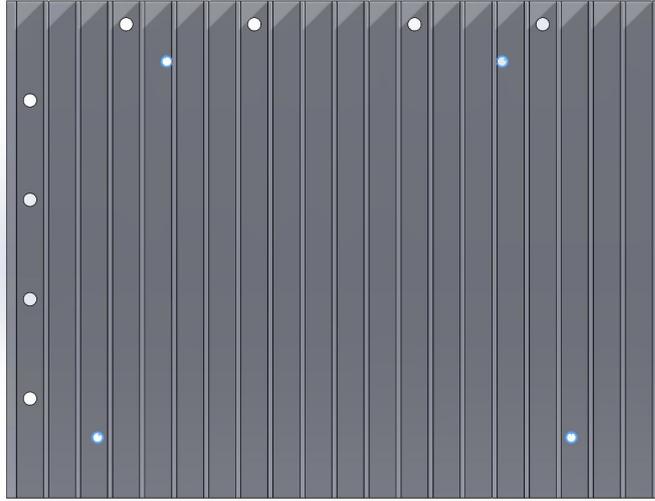


Figure 4.6: Heat Sink

For the assembly of the heat sink threaded holes were preferred over nuts due to the lack of space in between the fins of the heat sink. Furthermore the heat sink has got a thickness of 8mm which would be enough to fix the inverter with M5 screws. The holes highlighted in the Figure 4.6 are four threaded M5 holes for the mounting of the inverter on the heat sink. These holes were positioned so that they were as centered as possible and that they did not meet any of the fins of the heat sink. But that was not possible and the two top threads of the inverter are slightly skimming the fins. Nevertheless if during its manufacturing the fins are in this part broken it would not affect much its cooling capacity as the heat sink is a bit oversized. The rest of the threads are for the connection plates of the heat sink assembly to the framework. These were also placed in between the fins so that the heat sink was damaged as least as possible.

4.6 Adapter test motor

This test stand is going to be compatible for tests with and without a gearbox, so a third coupling for the testing of the motor alone would be needed but this would cost too much for the budget of this project. Therefore an adapter was designed for the shaft of the motor which is 7mm big. So the adapter consist on a cylinder with an outer diameter of 24mm so that it could fit the coupling previously selected and an inner diameter with a pressfit of 7mm so that it could

be introduced in the shaft of the motor and be able of transmitting the torque. In the figure below there is a picture of the adapter.

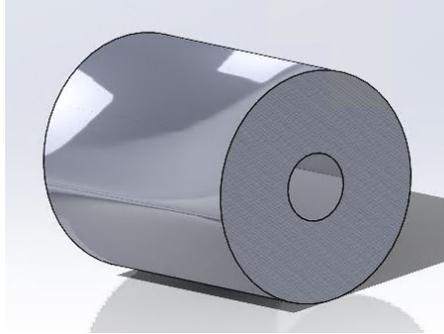


Figure 4.7: Adapter test motor

This solution will be cheaper than buying every time a new coupling for the new test machine that is desired to be tested. In future test this piece then will be needed to be redesigned for the new upcoming motors.

Chapter 5

Sustainable Development Goals

The Sustainable Development Goals refer to a series of goals or guidelines set by the UN, so that in the future we can have a much more stable, sustainable, and less damaging world for ourselves and future generations. To this end, 17 challenges were set in different areas, ranging from social, economic, and environmental issues.

Many countries and companies have joined this cause by committing themselves to making the necessary reforms to their current structures to be able to meet these goals by 2030.

As mentioned above, these challenges cover a large number of themes or sectors, and this project is related to some of them. This is the list of 17 areas which are targeted in the sustainable development goals:

1. No poverty
2. Zero hunger
3. Good health and well-being
4. Quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic worth
9. Industry, innovation and infrastructure
10. Reduced inequalities

11. Sustainable cities and communities
12. Responsible production and consumption
13. Climate action
14. Life below water
15. Life on land
16. Peace, justice and strong institutions
17. Partnership for the goals

The goal that is more addressed in this project would be the goal number 9 (Industry, innovation and infrastructure). The definition of this goal according to ONU's website is "Investment in infrastructure and innovation are crucial drivers of economic growth and development. With over half the world population now living in cities, mass transport and renewable energy are becoming ever more important, as are the growth of new industries and information and communication technologies". This goal of the ONU is looking to potentiate the innovation of new solutions against the climate change and promoting the energy efficiency.

As this project is targeted towards the development of a more efficient and cleaner car, we can deduct that this project is helping the development of cleaner solutions in transportation and challenging the climate change. This test bench will help to analyse how wefficient are the electric motors as well as how good are the motor controls that are going to be tested in this test rig. This translates in a direct saving in carbon emissions and a cleaner future transportation.

Chapter 6

Conclusions and future work

Almost all of the relevant information for the development, testing and measures of a electric motor are obtained with a test stand. At the present time the TUfast eco team do not have a test stand for their development of new prototypes and it is crucial in order to develop a good new generation of cars, even more taking into account that the competition rely on energy efficiency and not just power alone. This is why TUfast eco team is looking for a test stand for their future editions. Not only that but the TUfast eco team want to test the gearbox of the car which is also a very important part in the design for a high efficiency car. So this test stand has also to be compatible with the gearbox of the car.

The project of this test stand is divided in three thesis that are going to be developed by three different students: mechanical, electrical and software control. The selection of the electrical components was being done by another student who started one month later.

The objective of this master thesis was to do the design of a test stand for low power and high efficiency electric motors. The mechanical design process of the test stand is explained throughout this whole master thesis.

This test stand was design as a portable test stand that could be transported. Regarding the structure of the test stand it was made out of standard aluminium profiles and the whole system was built on top of a steel T-slot plate. This test stand also counts with a torque sensor taking the measures as well as a load machine. For the protection of the rotating parts, a steel cover was included as well in the design of the test bench. In relation to the gearbox in this document is also explained the adapter part for the gearbox so that the gearbox can be installed in the test stand.

Also in this thesis the fabrication process was taken into account and also the total costs of the construction as the budget is wanted to keep it as low as possible. In the annex of this thesis the fabrication drawings of the parts can be found.

This test stand will allow the team to take all the relevant measures that the team needs and it will help the team to develop better mechanical designs for the gearboxes, compare different electric motor solutions and develop as well better software controls for the motor.

The estimated total costs for the mechanical construction of this test stand are around 8500€. In the price is included all the principal element and an estimation of the material and fabrication costs of the own designed parts. The Table 6.1 shows the actual costs for every part, the estimated costs for the fabrication of the own design parts are around 500€.

Table 6.1: Price List

N ^o	Component	Company	Model	Quantity	€/unity
1	15kW Mahle motor + Inverter	Mahle	Antriebssystem 48V 15kW ASV7102	1	1.828,80
2	IT enclosure	Rittal	Rittal 7507.110 19 Zoll	1	305,00
3	Coupling Load Machine	HBK	24/24mm	1	600,00
4	T-nutenplatte	Vakuumtisch.de	T-slot plate 10050	1	1.579,00
5	Vibrationsdaempfer	Paulstra	40x40	4	13,40
6	Scharnier	Pinet	50x50x2	2	14,30
7	Heat Sink		Sevcon Gen4	1	60,91
8	Coupling Load Machine	HBK	24/28mm	1	600,00
9	Torque Sensor	HBM	T22	1	2.000,00
10	Framework	Maytec	Several	1	873,00

For the future steps, the assembly and fabrication of the actual test stand is to be done, once the other two thesis are finished. Then after the test stand is completely mounted a testing of the whole system is to be done and check if the results of the complete design meet the TUfast eco requirements.

Appendix A

Bill of Materials

A.1 Complete Bill of materials

Table A.1: Bill of materials

Pos.	Component	Company	Model	Quantity	€/unity
1	15kW Mahle motor + Inverter	Mahle	Antriebssystem 48V 15kW ASV7102	1	1.828,80
2	Box	Rittal	Rittal 7507.110 19 Zoll	1	305,00
3	Coupling Load Machine	HBK	24/24mm	1	600,00
4	T-nutenplatte	Vakuumtisch.de	T-slot plate 10050 Steel	1	1.579,00
5	Vibrationsdaempfer	Paulstra	40x40	4	13,40
6	Scharnier	Pinet	50x50x2	2	14,30
7	Heat Sink		Sevcon Gen4	1	60,91
8	Coupling Load Machine	HBK	24/28mm	1	600,00
9	Torque Sensor	HBM	T22	1	2.000,00
10	Framework	Maytec	Several	1	873,00
	Profile 40x40 150mm	Maytec	4 slots	2	
	Profile 40x40 920mm	Maytec	4 slots	2	
	Profile 40x40 440mm	Maytec	4 slots	3	
	Profile 40x80 600mm	Maytec	6 slots	4	
	Profile 40x80 920mm	Maytec	6 slots	4	
	Profile 80x80 760mm	Maytec	8 slots	4	
	Cover cap 40x40	Maytec		2	
	Cover cap 40x80	Maytec		8	
	Castor	Maytec	80kg	4	
	Cilindric head screw, M8x14	Maytec		8	
	Universal Connector	Maytec		44	
	M8 threaded plate	Maytec		8	
11	M8x30 Sechskantenschraube			4	
12	M10x50 Sechskantenschraube			4	
13	M4x20 Zylinderschraube			6	
14	M6x25 Sechskantenschraube			4	
15	M5x20 Zylinderschraube			12	
16	M4x16 Senkschrauben mit Innensechskant			4	
17	M8x20 Sechskantenschraube			4	
18	M8x20 Zylinderschraube			8	
19	M8x80 Sechskantenschraube			2	
20	M8x12 Zylinderschraube			12	
21	M4x8 Senkschrauben mit Schiltz			4	
22	M4 Sechskantmuttern Typ1			4	
23	M5x20 Sechskantenschraube			5	
24	M5x40 Zylinderschraube			2	
25	M5x45 Zylinderschraube			2	
26	M8x25 Sechskantenschraube			4	
27	M6x10 Zylinderschraube			12	
28	M6 Sechskantmuttern Typ1			8	
29	M8 T-nut		for T-slot plate	18	
30	M8 T-nut		for framework	24	

A.2 Trolley bill of materials

Design Title : Final TrolleyV2.1.scene
Revision Level :
Approved by :
Designer :
Company :
Address :
E-Mail :
Phone :
Date : 2022-07-23



Bill of materials (Number of kits: 1)

Pos	Article-No	Description	Units	Qty	Each €	Price €
1	1.11.040040.43LP-AA4A00/150	Profile 40x40, 4E, light, plain	MM	2	7.31	14.61
2	1.11.040040.43LP-AA4AAA/920	Profile 40x40, 4E, light, plain	MM	2	24.43	48.86
3	1.11.040040.43LP-AA4AAA/440	Profile 40x40, 4E, light, plain	MM	3	15.13	45.38
4	1.11.040080.64L-F00F00/600	Profile 40x80, 6E, light	MM	4	24.10	96.40
5	1.11.040080.64L-FB1FB1/920	Profile 40x80, 6E, light	MM	4	44.15	176.61
6	1.11.080080.83L-LD1L00/760	Profile 80x80, 8E, light	MM	4	64.46	257.85
7	1.42.20404.2	Cover cap 40x40, dia: 12, black	EA	2	1.19	2.38
8	1.42.20408.2	Cover cap 40x80, black	EA	8	1.77	14.16
9	1.45.12100	Fixed castor with fitting plate, dia: 100	EA	4	19.50	78.00
10	0.63.D06912.08014	Cylindric head screw, DIN 6912 - M8x14	EA	8	0.24	1.92
11	1.21.4E0	Connector, universal	EA	44	3.05	134.20
12	1.31.EM8	Threaded plate E, M8	EA	8	0.35	2.80

Total Weight: 35.31 kg (77.84 lbs) **Total (EURO):** € 873.19

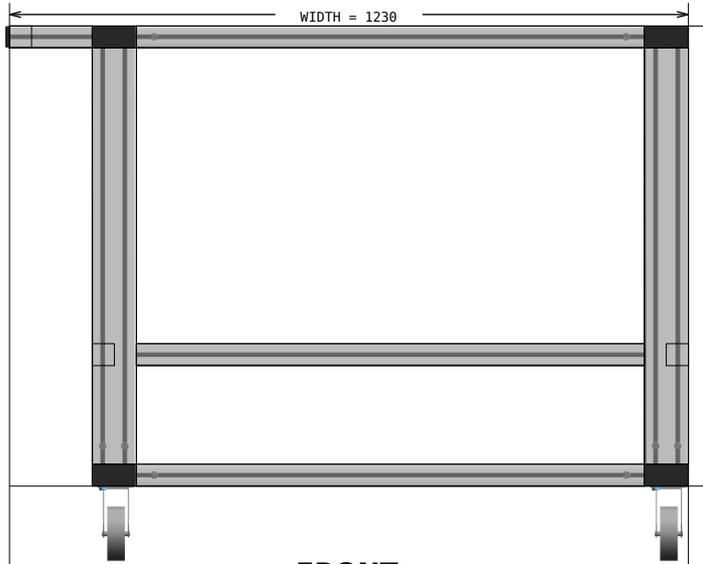
* The price indicated above, does not include assembly, packaging, taxes and transport.
 Additional costs can be incurred for:
 Machining per drawing, accessories small quantities per article, order processing, drawing review / redesign

Isometric view

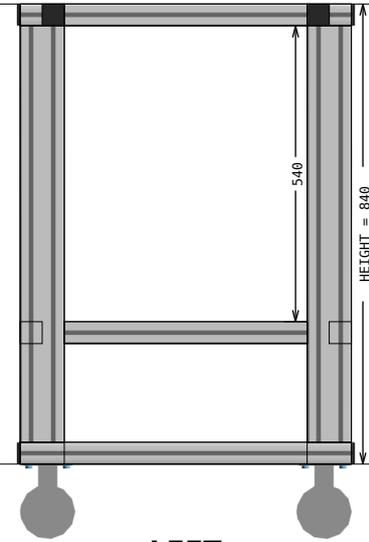
Some accessories may not be shown



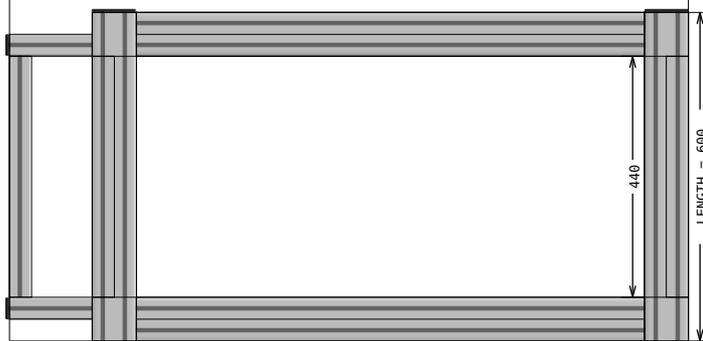
Multiview



FRONT



LEFT

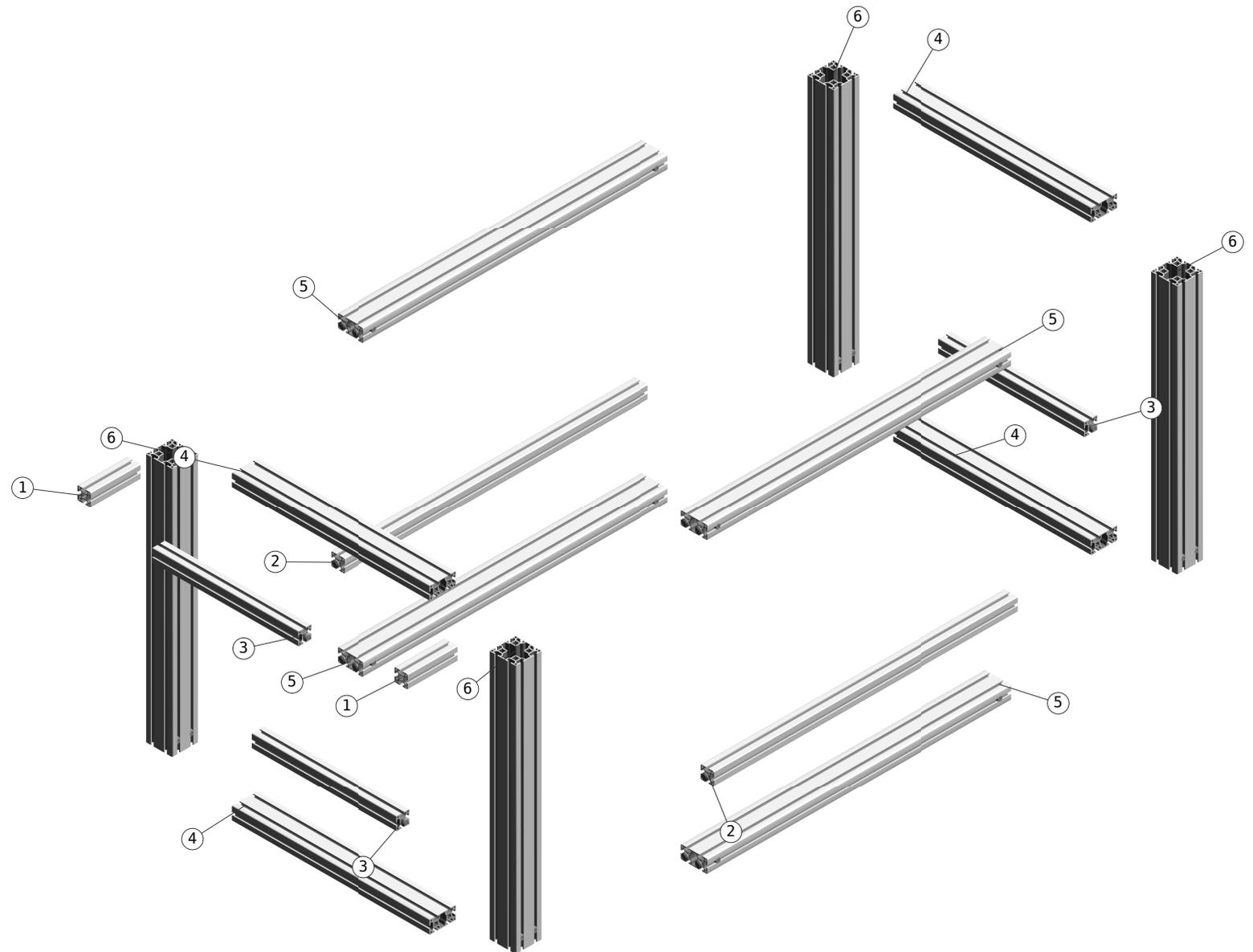


TOP



ISOMETRIC

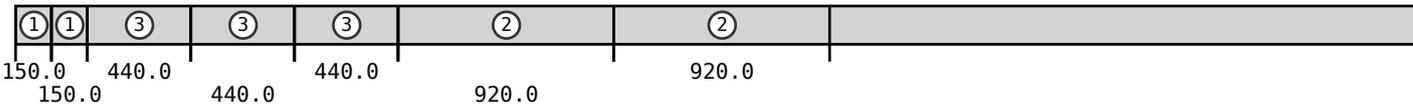
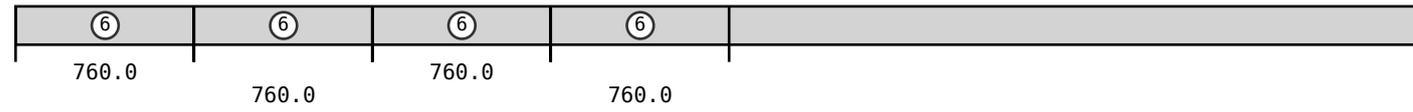
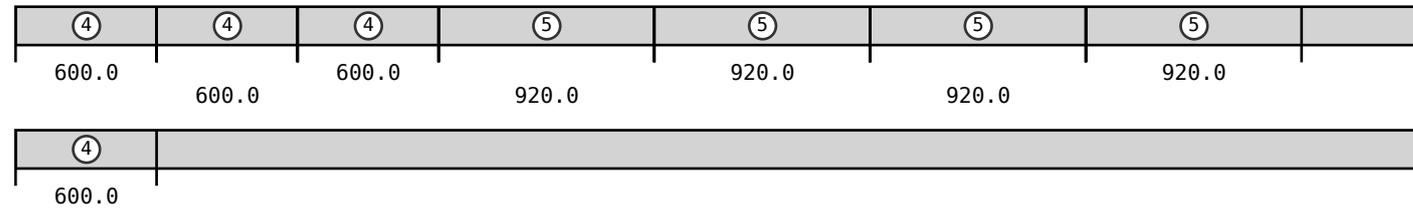
Exploded view



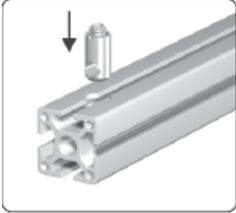
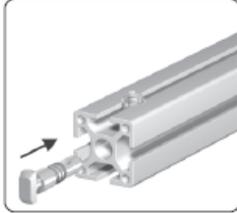
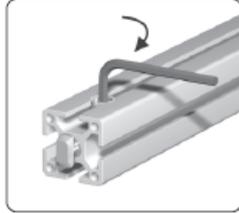
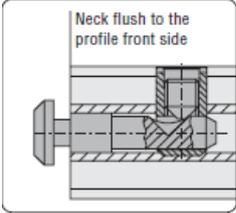
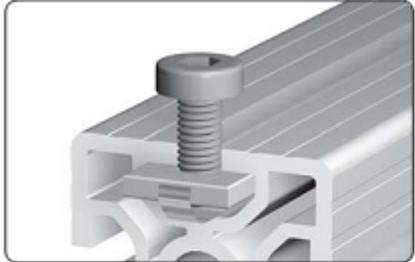
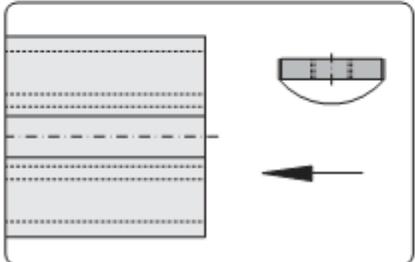
Assembly List

Pos	Article-No	Description	Related parts	Qty
1	1.11.040040.43LP-AA4A00/150	Profile 40x40, 4E, light, plain	1.21.4E0, Connector, universal	2
2	1.11.040040.43LP-AA4AAA/920	Profile 40x40, 4E, light, plain	1.21.4E0, Connector, universal	4
3	1.11.040040.43LP-AA4AAA/440	Profile 40x40, 4E, light, plain	1.21.4E0, Connector, universal	6
5	1.11.040080.64L-FB1FB1/920	Profile 40x80, 6E, light	1.21.4E0, Connector, universal	16
6	1.11.080080.83L-LD1L00/760	Profile 80x80, 8E, light	1.21.4E0, Connector, universal	16
9	1.45.12100	Fixed castor with fitting plate, dia: 100	0.63.D06912.08014, Cylindric head screw, DIN 6912 - M8x14 1.31.EM8, Threaded plate E, M8	8 8

Suggested profile cuts (incl. kerf: 3.5 mm)

Article-No	Cuts	Waste (mm)
1.11.040040.43LP		2515.5 mm
1.11.080080.83L		2946.0 mm
1.11.040080.64L		495.5 mm 5396.5 mm

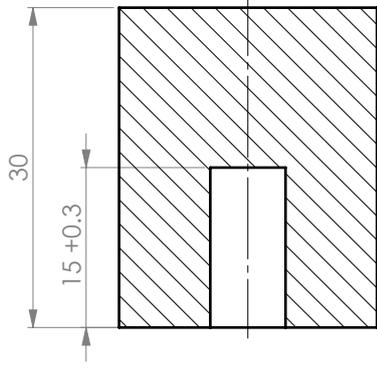
Assembly hints

CONNECTOR	1.21.4E0	Connector, universal	
<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;">  <p>Insert the cross bushing</p> </div> <div style="text-align: center;">  <p>Push in the anchor</p> </div> <div style="text-align: center;">  <p>Pretension the anchor</p> </div> </div> <div style="margin-top: 10px;">  <p style="font-size: small;">Neck flush to the profile front side</p> <p>Comments For the optimal assembly of the profiles the connector is to be installed in such a way that the neck is flush to the profile front side</p> </div>			<p>Most MayTec connectors follow these assembly steps. Tightening torque is: 5-15 Nm for 20mm profiles, 30 Nm for 30mm group, 35 Nm for 40mm and larger profiles.</p>
None	1.31.EM8	Threaded plate E, M8	
<div style="display: flex; justify-content: space-between;"> <div style="width: 30%;">  <p>Fixed into position with leaf spring</p> </div> <div style="width: 60%;"> <p>Application Fastening element for screw-type connections</p> </div> </div> <div style="margin-top: 10px;">  <p>Assembly Insert from end</p> </div>			<p>These plates must be inserted from the open side of the profile, prior to final frame assembly</p>

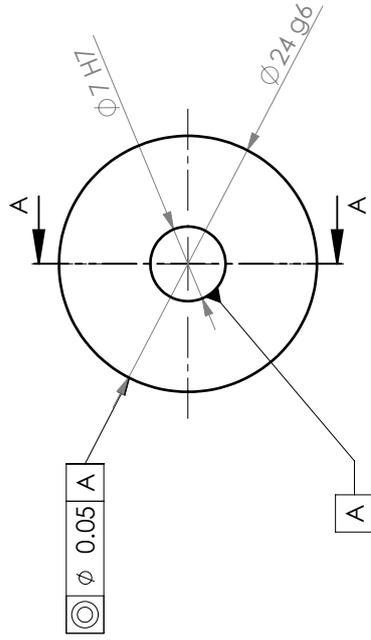
Appendix B

Drawings

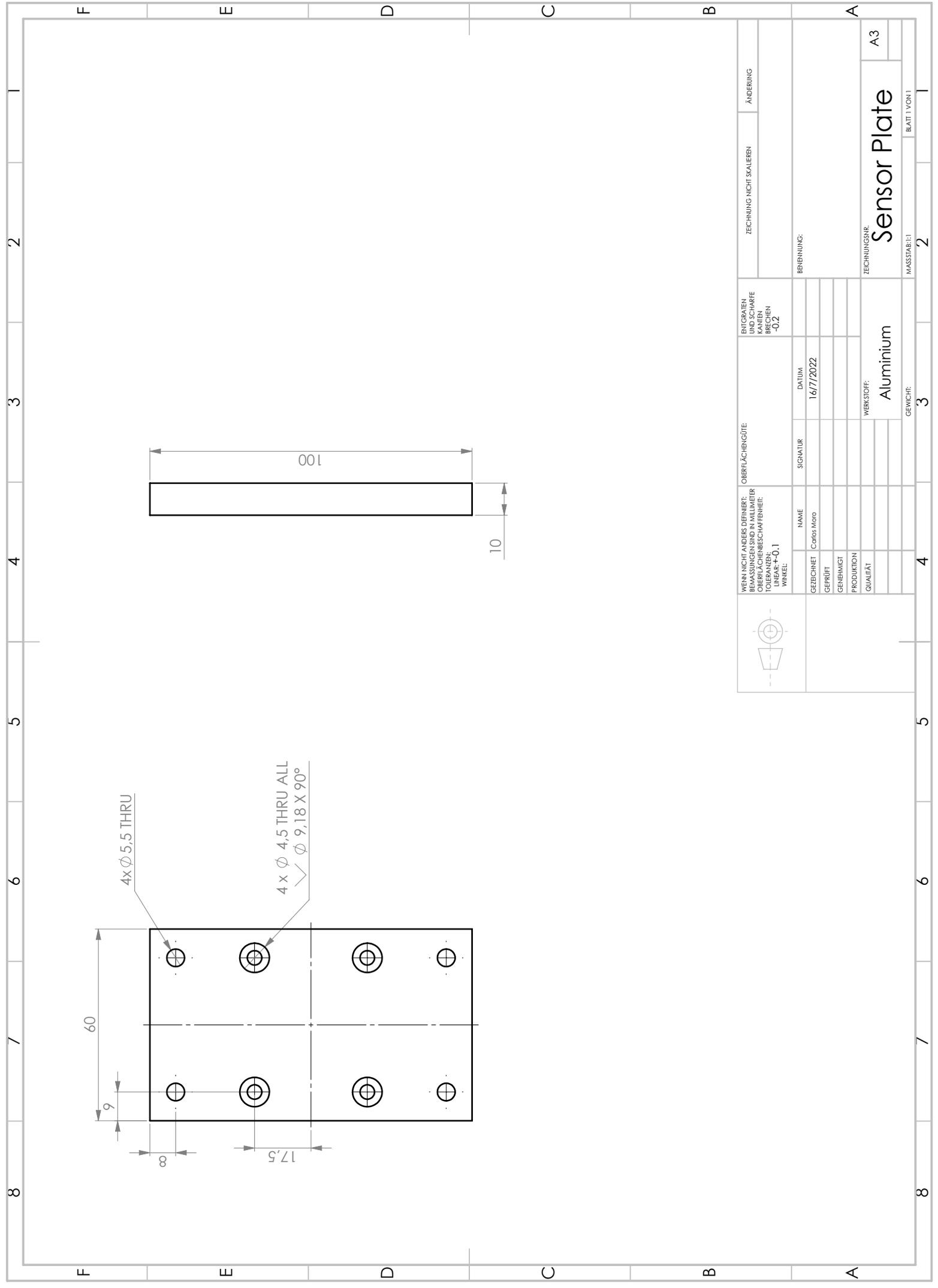
B.1 Own Design Parts



SECTION A-A



		WENN NICHT ANDERS DERNERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNGRAD: +0.1 WINKEL:	OBERFLÄCHENGÜTE: 	ENTGRATEN UND SCHARFE KANTEN BRECHEN -0.2	ZEICHNUNG NICHT SKALIEREN 	ÄNDERUNG
GEZEICHNET: Carlo's Moro GEPRÜFT: GENEHMIGT: PRODUKTION: QUALITÄT:	NAME: Carlo's Moro SIGNATUR: WERKSTOFF: Stahl S-355	DATUM: 19/7/2022	BEKENNUNG: 	ZEICHNUNGSNR. Adapter Motor A3	MASSSTAB: 2:1 2	BLATT 1 VON 1
GEWICHT: 3		4	3	2	1	1



4x \varnothing 5,5 THRU

4 x \varnothing 4,5 THRU ALL
 \sphericalangle \varnothing 9,18 X 90°

60

9

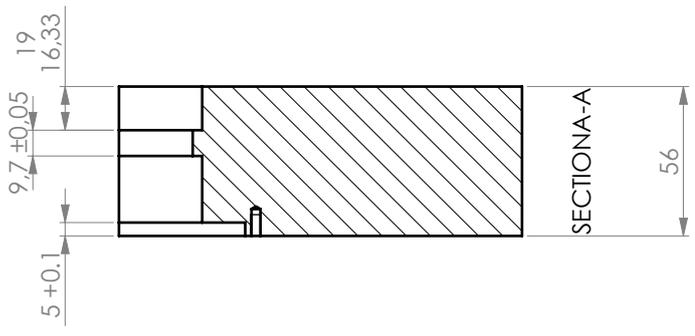
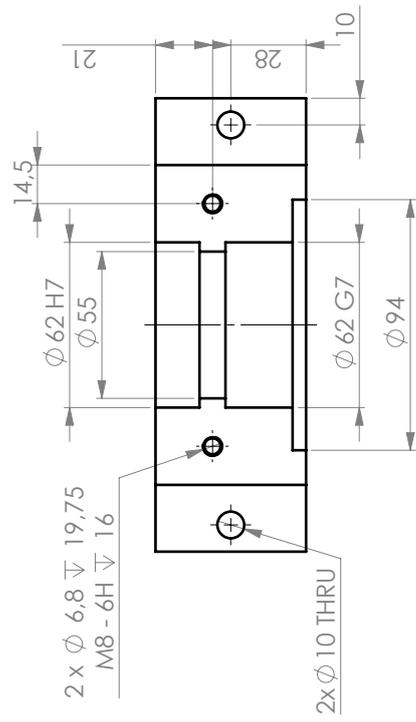
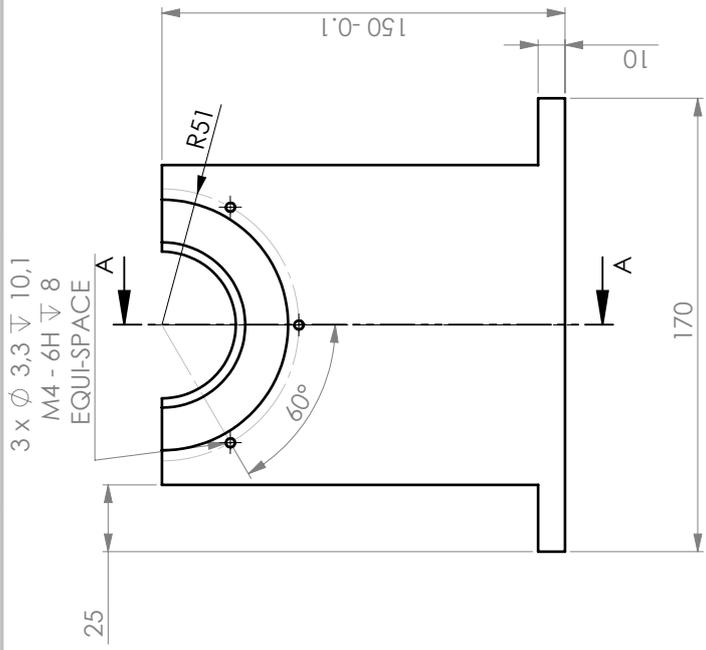
8

17,5

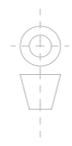
100

10

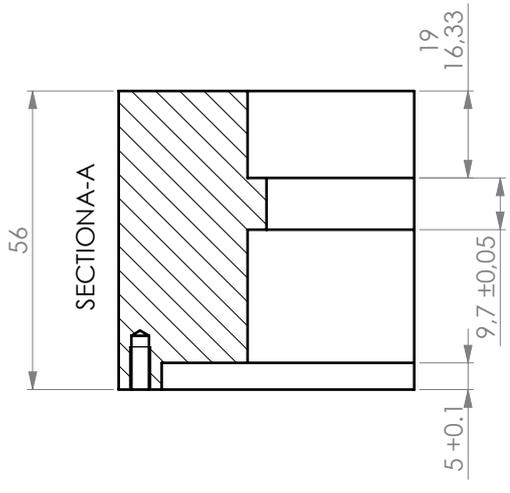
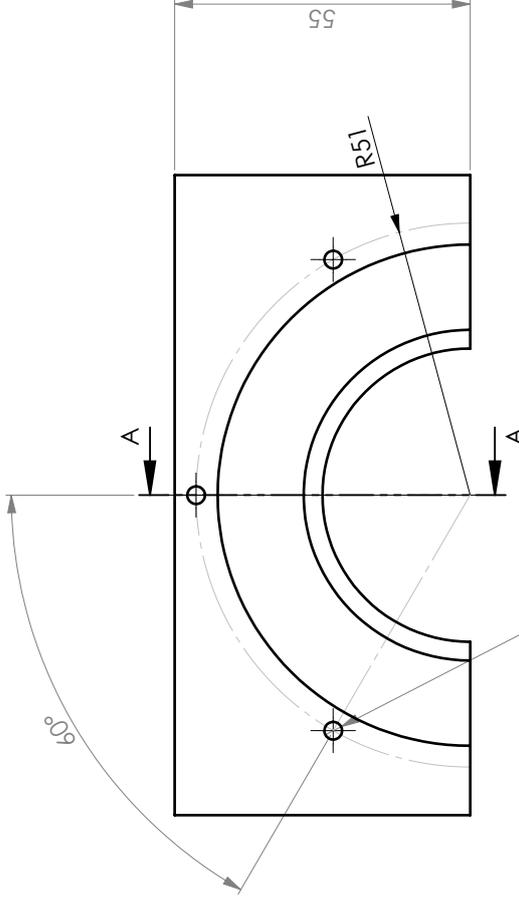
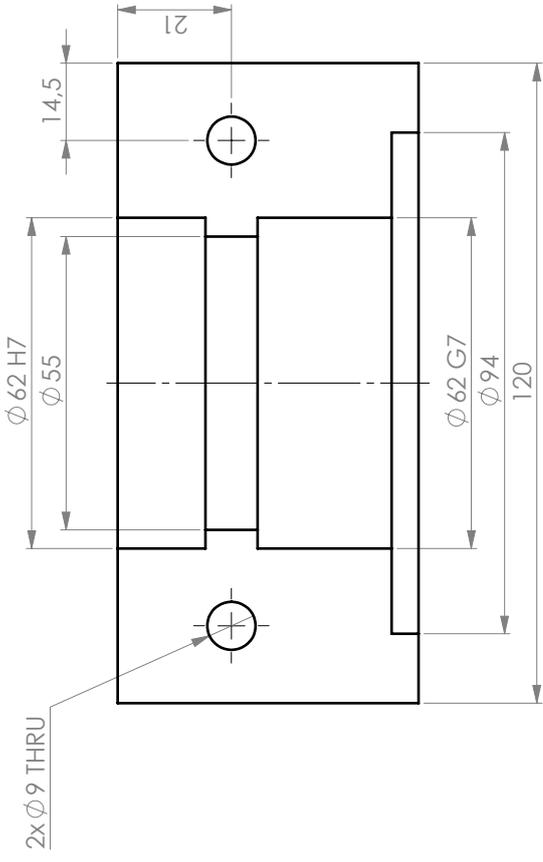
	WENN NICHT ANDERS DERNIERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNRAU: -R0,1 WINKEL:	OBERFLÄCHENGÜTE: NAME: Corbis Miro DATUM: 16/7/2022	BRITGRATEN UND SCHARFE KANTEN BRECHEN -0,2	ZEICHNUNG NICHT SKALIEREN ÄNDERUNG
	GEZEICHNET: Corbis Miro GEPRÜFT: GENEHMIGT: PRODUKTION: QUALITÄT:	SIGNATUR: WERKSTOFF: Aluminium	BEZEICHNUNG: Sensor Plate	ZEICHNUNGSNR. A3
GEWICHT: 3		MASSSTAB: 1:1		BLATT 1 VON 1



Teil muss mit dem Gegenteil (Bearing Holder 2)
zusammen gebohrt werden

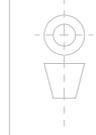


WENN NICHT ANDERS DERNERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNGERÄT: -0,1 WINKEL:		OBERFLÄCHENGÜTE:		BRITGRATEN UND SCHARFE KANTEN BRECHEN -0,2		ZEHNUNG NICHT SKALIEREN		ÄNDERUNG	
GEZEICHNET	Corbis Moro	NAMME	SIGNATUR	DATUM	BENENNUNG:				
GEPRÜFT					16/7/2022				
GENEHMIGT									
PRODUKTION									
QUALITÄT					WERKSTOFF: Stahl S-355				
								ZEHNUNGSNR. A3	
								MASSTAB: 1:2	
								GEWICHT: 3	
								BLATT 1 VON 1	

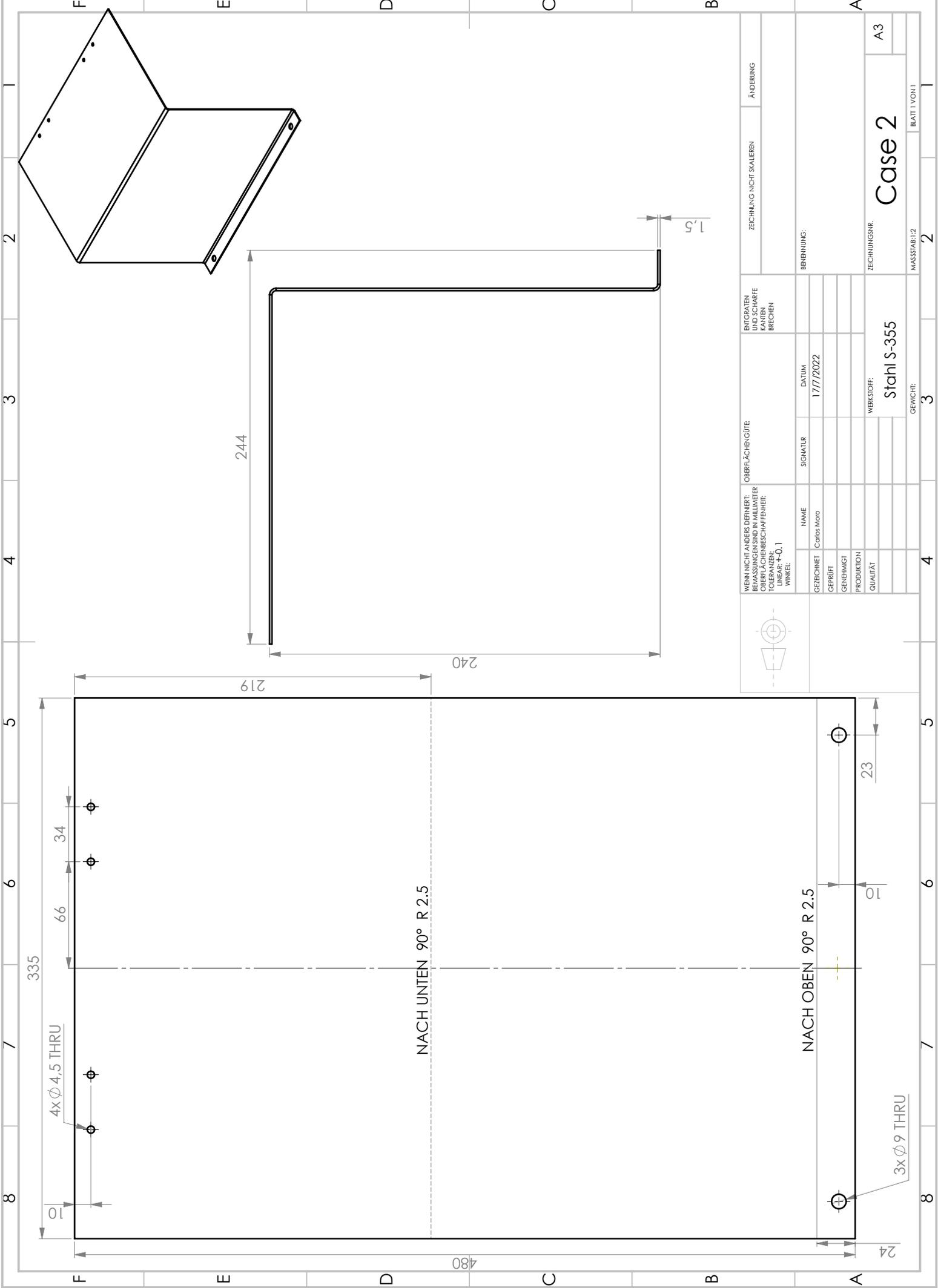


Teil muss mit dem Gegenteil (Bearing Holder 1) zusammen gebohrt werden

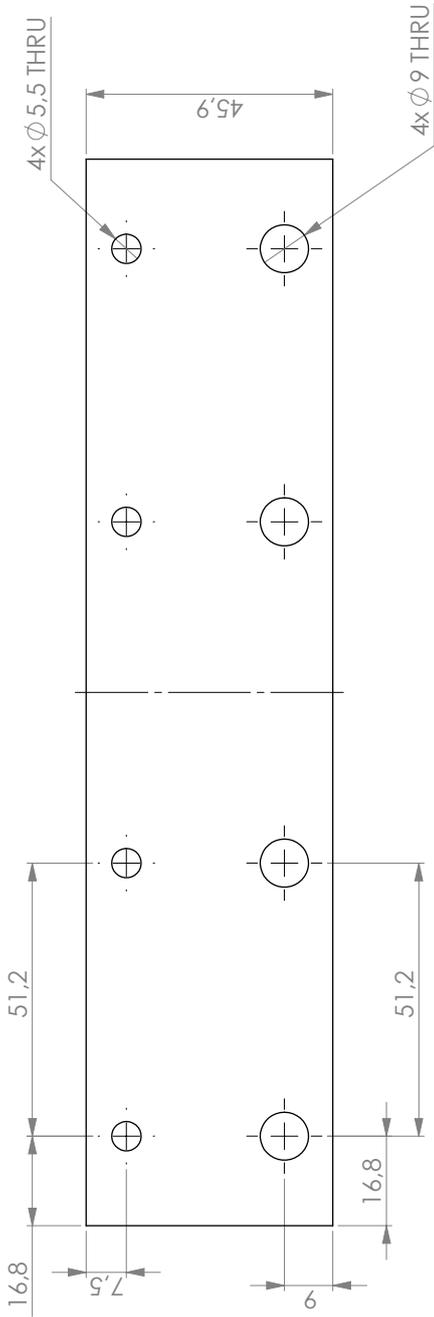
Ø 3,3 √ 10,1
M4 - 6H √ 8
EQUI-SPACE



WENN NICHT ANDERS DERNERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: TOLERANZ: UNPAR.: +0.1 WINKEL:		OBERFLÄCHENGÜTE:		BRITGRATEN UND SCHÄRFE KANTEN BRECHEN -0.2		ZEICHNUNG NICHT SKALIEREN		ÄNDERUNG	
GEZEICHNET	NAME	SIGNATUR	DATUM	BENENNUNG:					
GEPRÜFT	Carlo's Moro		17/7/2022						
GENEHMIGT									
PRODUKTION									
QUALITÄT									
				WERKSTOFF:		Stahl S-355		ZEICHNUNGSNR. A3	
				GEWICHT:		3		BLATT 1 VON 1	
						2		Bearing Holder2	
								MASSTAB: 1:1	

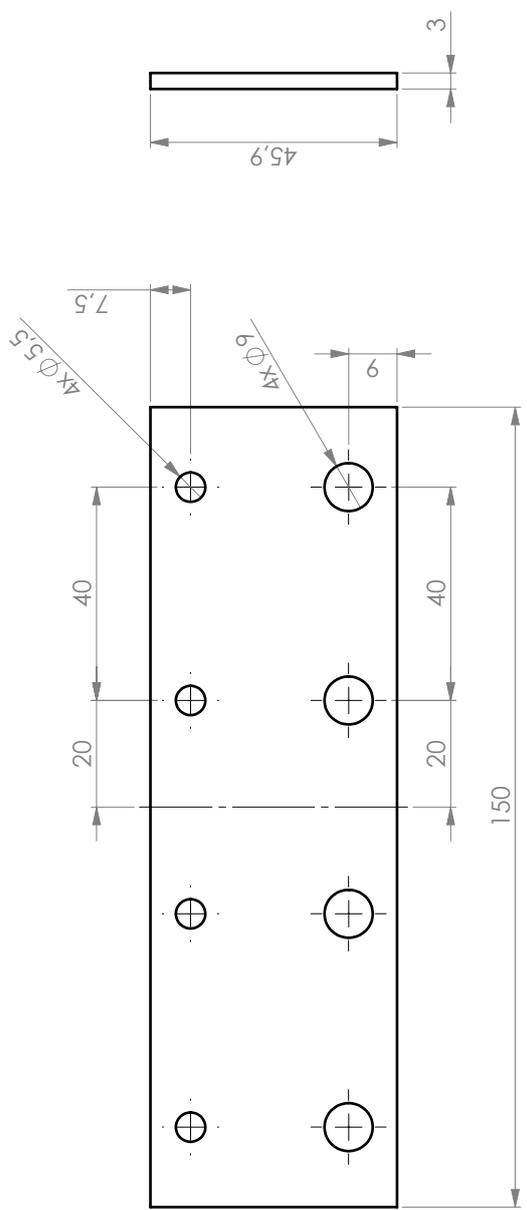


WENN NICHT ANDERS DERNERT: BEWASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: TOLERANZEN: LUNGEN: +0, -0,1 WINKEL:	NAME	SIGNATUR	DATUM	ENTGRATEN UND SCHARFE KANTEN BRECHEN	ZECHNUNG NICHT SKALIEREN ÄNDERUNG
	GEZEICHNET: Carlos Moro GEPRÜFT GENEHMIGT PRODUKTION QUALITÄT				
OBERFLÄCHENGÜTE:				BEKENNUNG:	ZECHNUNGSNR. Case 2
WERKSTOFF:					
NACH UNTEN 90° R 2.5				GEWICHT: 3	BLATT 1 VON 1
NACH OBEN 90° R 2.5				A3	2

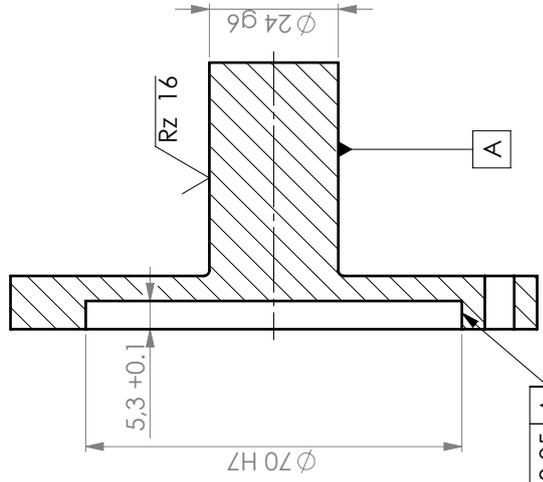
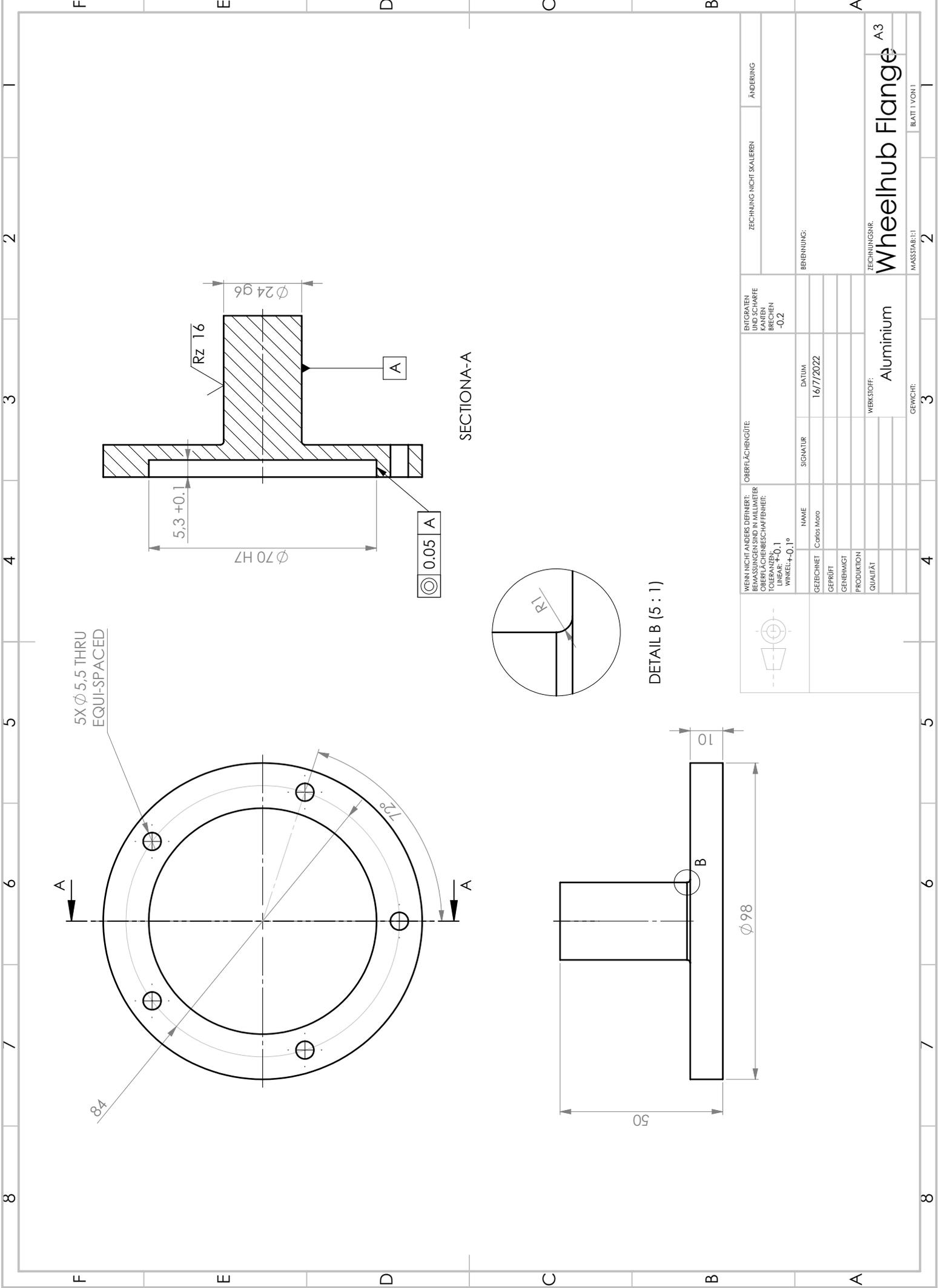


WENN NICHT ANDERS DERNIERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: TOLERANZEN: LINDAR: +0,1 WINKEL:	NAME	SIGNATUR	DATUM	ENTGRATEN UND SCHARFE KANTEN BRECHEN	ZEICHNUNG NICHT SKALIEREN	ÄNDERUNG
	GEZEICHNET: Corbis Moro GEPRÜFT GENEHMIGT PRODUKTION QUALITÄT					
OBERFLÄCHENGÜTE:				BEKENNUNG:		
WERKSTOFF:				ZEICHNUNGSNR.		
Stahl S-355				Inverter Plate 1		
GEWICHT:				MASSSTAB: 1:1		
3				2		
4				1		

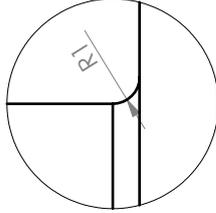
Blatt 1 von 1



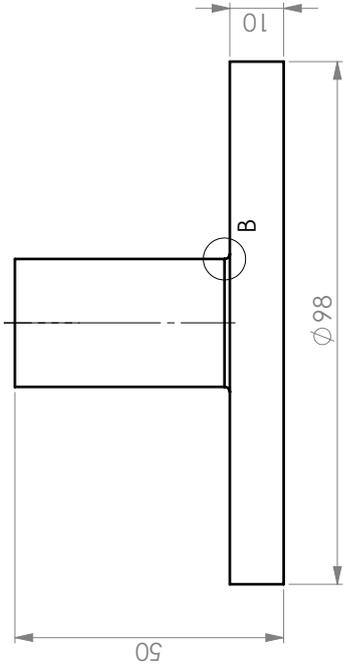
	WENN NICHT ANDERS DERNIERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNRAUH-0,1 WINKEL:		OBERFLÄCHENGÜTE: SIGNATUR DATUM		ENTGRATEN UND SCHARFE KANTEN BRECHEN		ZEICHNUNG NICHT SKALIEREN ÄNDERUNG	
	GEZEICHNET: Carls Moro GEPRÜFT: GENEHMIGT: PRODUKTION: QUALITÄT:	NAME: SIGNATUR: DATUM:	16/7/2022	BEKENNUNG: Stahl S-355 WERKSTOFF:		ZEICHNUNGSNR. Inverter Plate 2 A3		MASSSTAB: 1:1 2 BLATT 1 VON 1



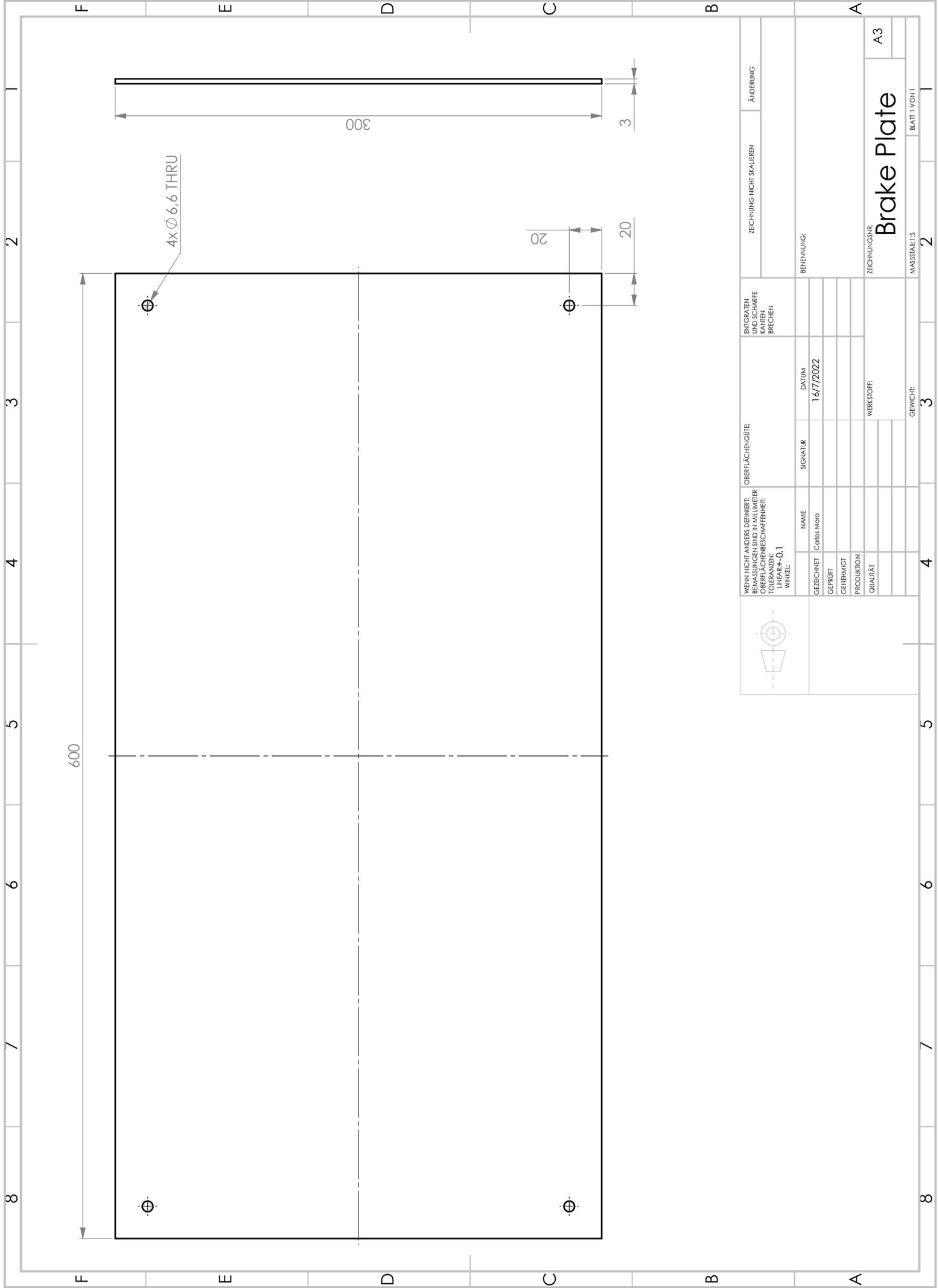
SECTION A-A



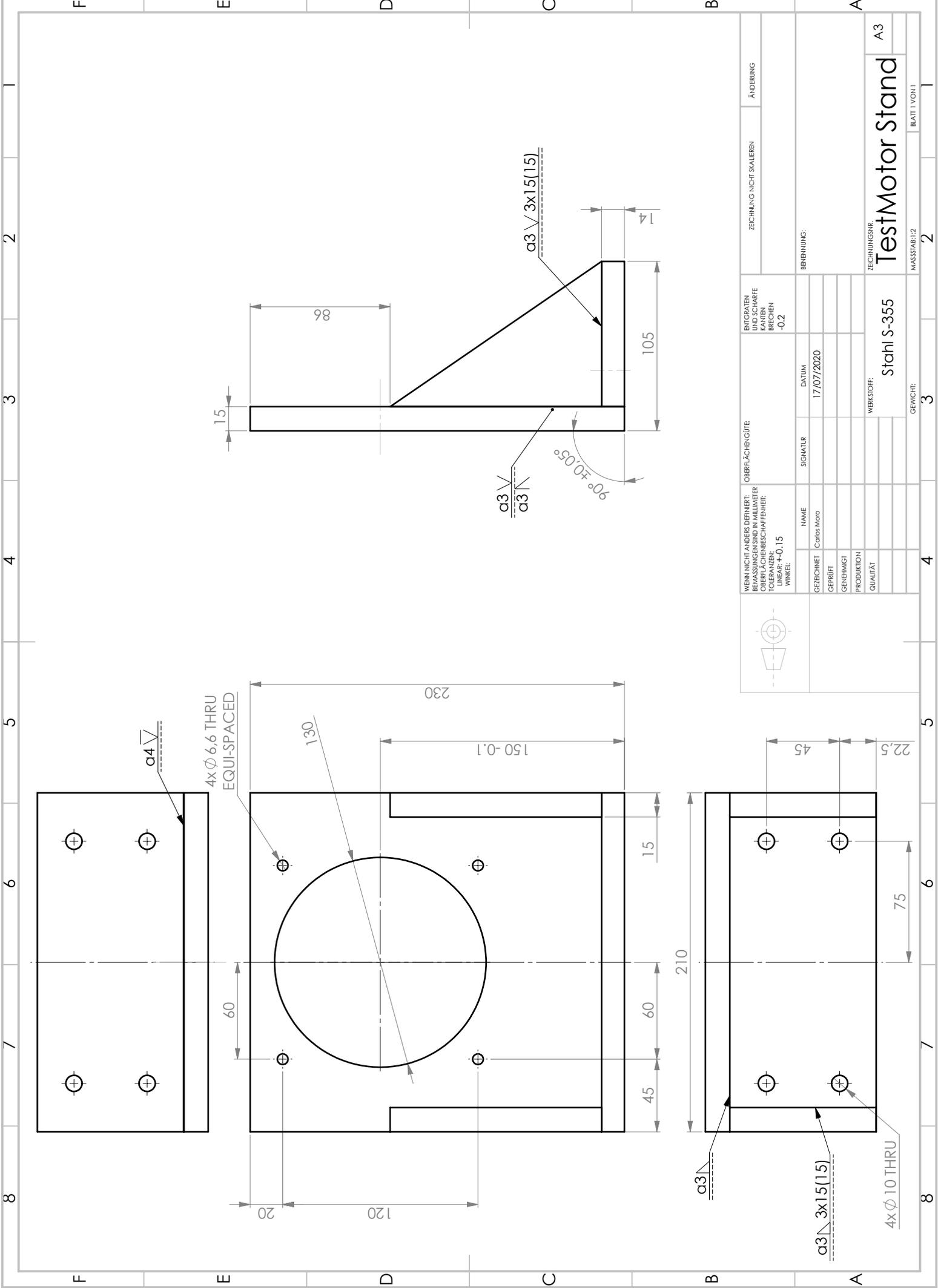
DETAIL B (5 : 1)



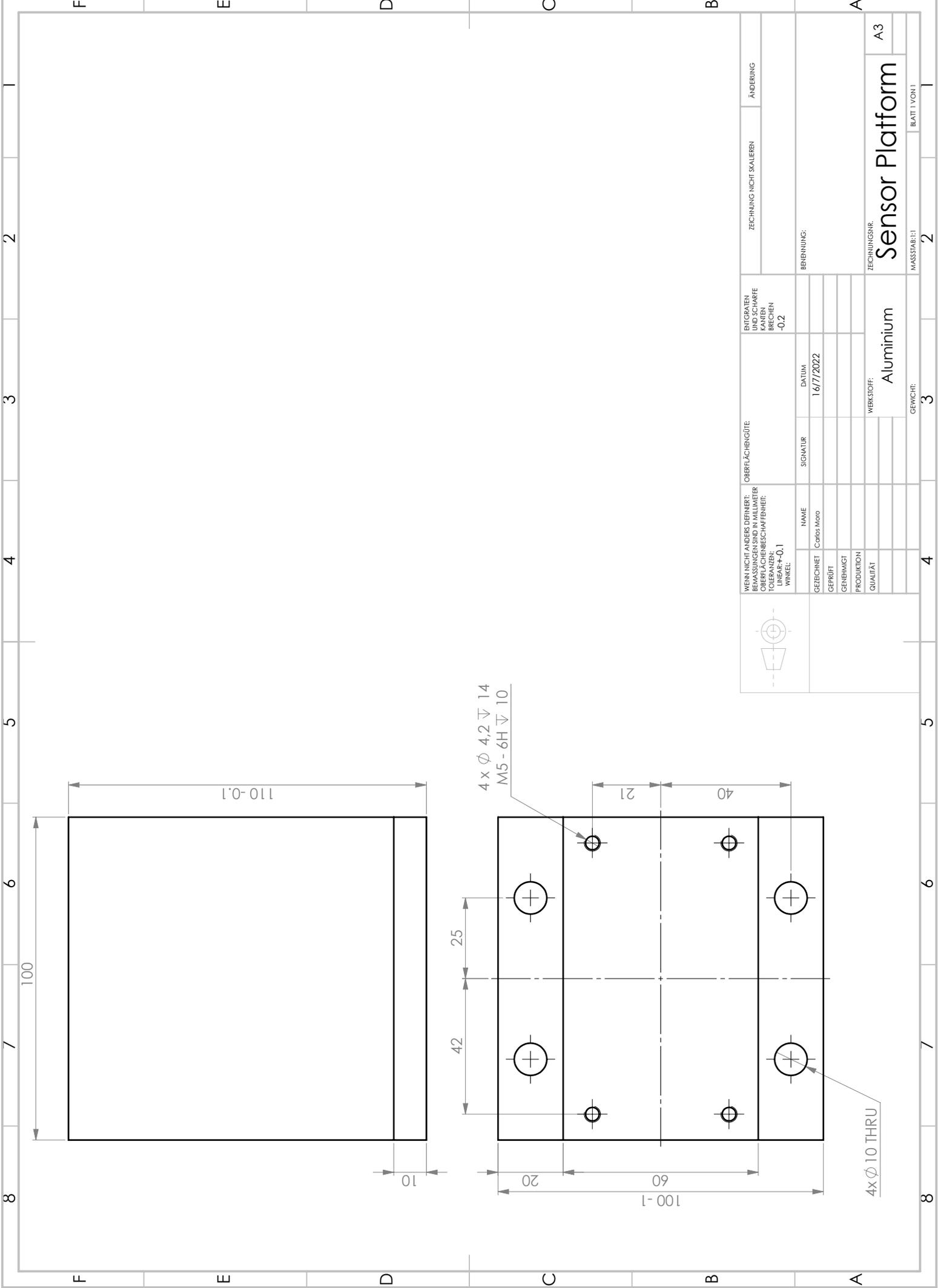
WENN NICHT ANDERS DERNIERT: BEWASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNIPAR: -0,1 WINKEL: +0,1°		OBERFLÄCHENGÜTE:		BRITGRATEN UND SCHARFE KANTEN BRECHEN -0,2		ZEICHNUNG NICHT SKALIEREN		ÄNDERUNG	
GEZEICHNET: Carlo's Moro	NAME: Carlo's Moro	SIGNATUR:	DATUM: 16/7/2022	BEZEICHNUNG:		ZEICHNUNGSNR.		WERKSTOFF:	
GEPRÜFT:	GENEHMIGT:	PRODUKTION:	QUALITÄT:	Aluminium		Wheelhub Flange A3		MASSSTAB: 1:1	
GEWICHT: 3				BLATT 1 VON 1		2		1	



		WENN NICHT ANDERS DERNIERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNRAUH-0,1 WINKEL:		OBERFLÄCHENGÜTE: NAME: Carlos Moro SIGNATUR:		DATUM: 16/7/2022		BRITGRATEN UND SCHARFE KANTEN BRECHEN		ZECHNUNG NICHT SKALIEREN		ÄNDERUNG	
GEZEICHNET:		NAME: Carlos Moro		SIGNATUR:		DATUM: 16/7/2022		BEKENNUNG:		ZECHNUNGSNR.		A3	
GEPRÜFT:		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	
GENEHMIGT:		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	
PRODUKTION:		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	
QUALITÄT:		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	
WERKSTOFF:		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	
GEWICHT:		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	
MASSSTAB: 1:5		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	
BLATT 1 VON 1		NAME:		SIGNATUR:		DATUM:		BEKENNUNG:		ZECHNUNGSNR.		A3	

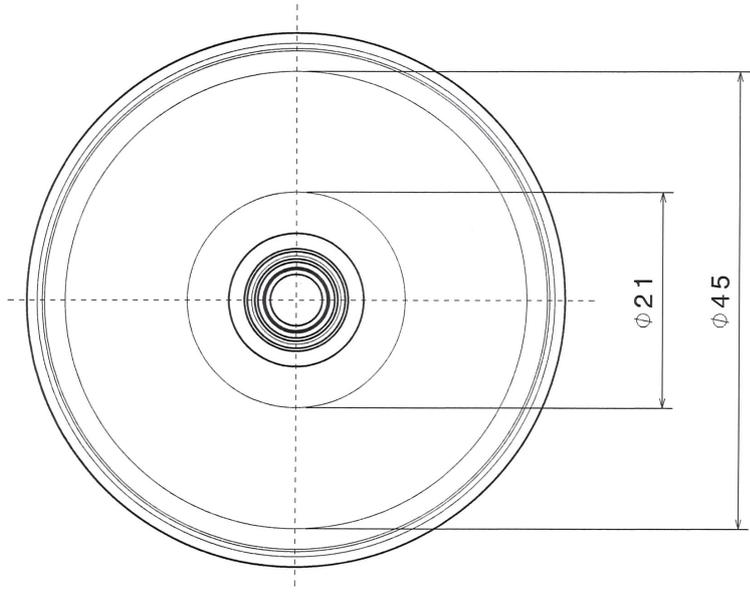
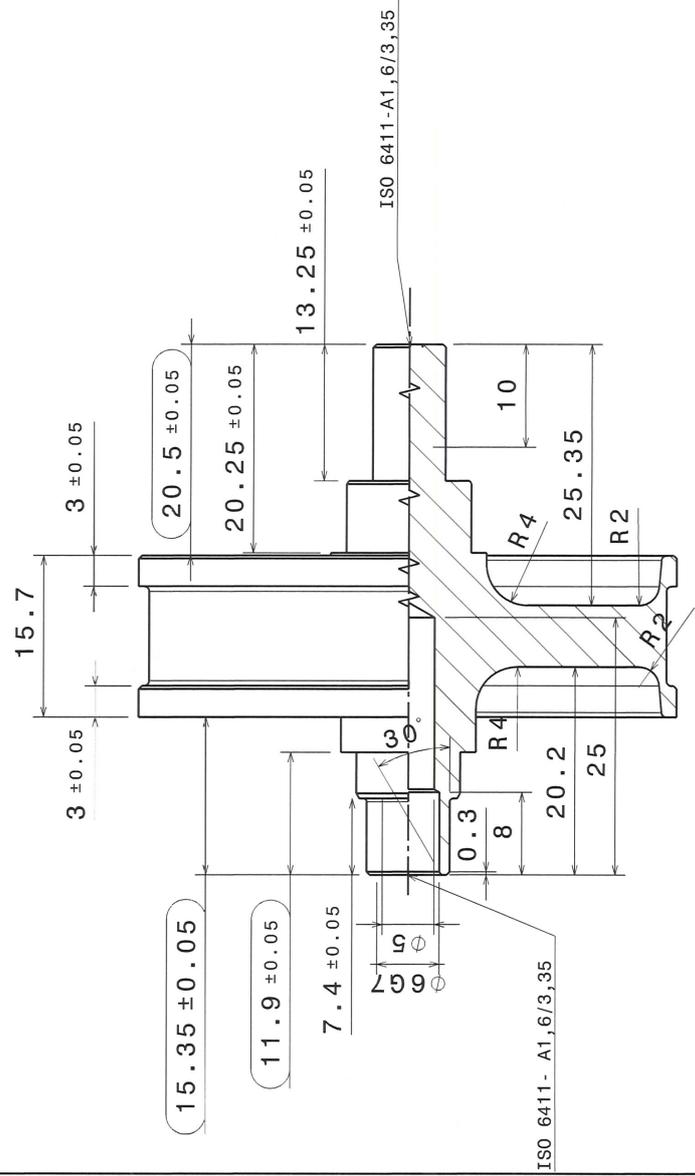
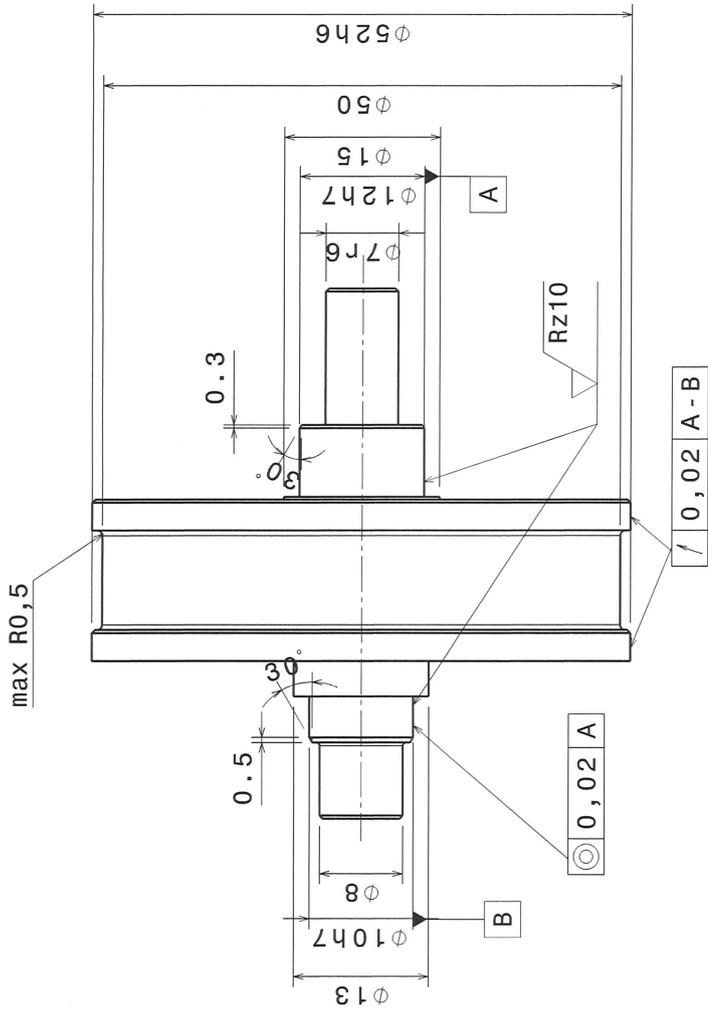


WENN NICHT ANDERS DERNERT: BEMASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNRAU: +0,15 WINKEL:		OBERFLÄCHENGÜTE: NAME: Corbis Moro DATUM: 17/07/2020 SIGNATUR:		BRITGRATEN UND SCHARFE KANTEN BRECHEN -0,2		ZEICHNUNG NICHT SKALIEREN ÄNDERUNG:	
GEZEICHNET	GENEHMIGT	PRODUKTION	QUALITÄT	BEZEICHNUNG: Stahl S-355 WERKSTOFF:		BEZEICHNUNG: TestMotor Stand A3	
GEWICHT: 3		MASSSTAB: 1:2		BLATT 1 VON 1		2	



		WENN NICHT ANDERS EBENIERT: BEWASSUNGEN SIND IN MILLIMETER OBERFLÄCHENBESCHAFFENHEIT: UNRAU: +0.1 WINKEL:		OBERFLÄCHENGÜTE: NAME: Carlo's Moro SIGNATUR:		BRITGRATEN UND SCHARFE KANTEN BRECHEN BRECHEN -0.2		ZEICHNUNG NICHT SKALIEREN ÄNDERUNG:	
GEZEICHNET: Carlo's Moro GEFÜHRT:		DATUM: 16/7/2022		BEZEICHNUNG:		BEZEICHNUNG:		BEZEICHNUNG:	
GENEHMIGT:		WERKSTOFF: Aluminium		ZEICHNUNGSNR.		ZEICHNUNGSNR.		ZEICHNUNGSNR.	
PRODUKTION QUALITÄT:		GEWICHT: 3		MASSSTAB: 1:1		MASSSTAB: 1:1		MASSSTAB: 1:1	
4		3		2		2		2	
8		7		6		5		4	
A		B		C		D		E	
A3		Sensor Platform		Sensor Platform		Sensor Platform		Sensor Platform	

B.2 Test Motor Shaft



Artikel-Nr.	263889	And. Zust.		SPN	SCHWARZ PRÄZISION
SPN-Zeichnungs-Nr.	18-47.000-1-12-10-3	Datum	6.12.21		
Fertigungszeichnung Blatt	001	Name	378 RB		

FAST		Alle unbemittelten Fasen 0,3x45°		Maßstab:	2:1	Gewicht:	xx g
Allgemein-Toleranzen	ISO 2768-FH	ISO 1302		Werkstoff:	Aluminium		
Bearb.	12.12.21	Z. Aydin		Rotorwelle			
Gepr.	00.00.00	Teamleiter					
Norm							
Zust							
Änderung							
Datum							
Name							
				Zeynep Aydin			Blatt
				015789035836			1
				Z.aydin@tufast.de			1 Bl.

B.3 Wheelhub

Bibliography

- [1] NASA. *Climate Change: How Do We Know?* 2022. URL: <https://climate.nasa.gov/evidence/#:~:text=Earth's%20climate%20has%20changed%20throughout,era%20%E2%80%94%20and%20of%20human%20civilization>. (visited on 07/01/2022).
- [2] United Nations Climate Change. *The Paris Agreement*. 2015. URL: <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement> (visited on 06/15/2022).
- [3] IEA. *Greenhouse Gas Emissions from Energy: Overview*. 2021. URL: <https://www.iea.org/reports/greenhouse-gas-emissions-from-energy-overview> (visited on 07/03/2022).
- [4] Transport & Environment. *Carmakers' electric car plans across Europe*. 2019.
- [5] Shell. *Über den Shell Eco Marathon*. 2022. URL: <https://www.shell.de/ueber-uns/initiativen/shell-eco-marathon.html> (visited on 06/27/2022).
- [6] W. Huang. *Electrical and electronic design of the test bench for Low-Voltage/Low Power electric machines*. 2016.
- [7] imc Test & Measurement GmbH. *Standard Test Stand Design*. 2022. URL: <https://www.imc-tm.com/products/test-stands/realized-test-stands/development-test-stands-for-e-motors/> (visited on 06/27/2022).
- [8] IHK für Oberfranken. *Grundlagen der Leistungselektronik*.
- [9] Verband der Elektrotechnik Elektronik Informationstechnik (VDE). *Errichten von Niederspannungsanlagen Schutzmaßnahmen – Schutz gegen elektrischen Schlag*. 2018.
- [10] Deutsche Institut für Normung (DIN). *Türen - Türen für den Wohnungsbau - Türblattgrößen, Bandsitz und Schlosssitz - Gegenseitige Abhängigkeit der Maße*. 2014.

BIBLIOGRAPHY
