CAGE DRONE ROBOT DESIGN FOR INSPECTION IN FUSION REACTOR

Lappeenranta–Lahti University of Technology LUT
Bachelor's Degree Programme in Mechanical Engineering, Bachelor's thesis
Bachelor’s Programme in Technology and Engineering Science
2024
Evgeniia Efimenko
Examiner: Adjunct Professor Tapio Saarelainen

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Energy Systems
Mechanical Engineering

Evgeniia Efimenko

Cage drone robot design for inspection in fusion reactor

Bachelor's thesis
2024
37 pages, 9 figures, 6 tables and 4 appendices
Examiner: Adjunct Professor Tapio Saarelainen

Tokamak fusion reactors stand at the forefront of achieving sustainable nuclear fusion energy. However, their operational environment presents significant challenges for inspection with traditional industrial robots. This bachelor's thesis aims to address these limitations with a compact, lightweight, and protected cage drone robot tailored for remote inspection tasks within the tokamak fusion reactor.

The paper derives critical requirements for a robotic drone system through a combination of Literature Review, 3D modelling, and Finite Element Analysis, explores its feasibility, and proposes a novel robot design. The study acknowledges its scope and limitations, omitting considerations of high radiation and temperature levels within the vacuum vessel of the tokamak reactor. The resulting 3D SolidWorks models, FE analysis results, and supporting documentation of the cage drone robot propose an innovative design to expand the inspection practices within tokamak fusion reactors, contributing to the realization of fusion energy as a viable and sustainable power source for the future.

Keywords: Cage drone robot, Inspection, Fusion reactor, Tokamak, Maintenance.

ACKNOWLEDGEMENTS

I would like to thank my family, friends, and Associate Professor Michael Child for the immense support throughout my thesis adventure.

Note: I acknowledge the use of the Grammarly tool [https://app.grammarly.com/] to enhance the writing style and composition (e.g. readability, clarity, and structure) of this paper. The tool was also used to check spelling, grammar, and punctuation of the text.

SYMBOLS AND ABBREVIATIONS

Roman characters

R	major radius	[m]
A	cross-section area	[m^2]
V	plasma volume	[m^3]
a	minor radius	[m]
N	unit of force	[N]
W	weight	[kg]
V	volume	[m^3]
d	density	[kg/m^3]

Greek characters

π	pi

Abbreviations

ITER	International Thermonuclear Experimental Reactor
CFETR	China Fusion Engineering Test Reactor
EU DEMO	European Union Demonstration Fusion Power Plant
UAV	Unmanned Aerial Vehicle
RH	Remote Handling
CEA	French Atomic Energy Commission
AIA	Articulated Inspection Arm
FIVI	Flexible In-Vessel Inspection
MIT	Massachusetts Institute of Technology
PAC	Porteur Articule´ en Cellule
3D	3 (Three) Dimensional
CAD	Computer-Aided Design
HVAC	Heating, Ventilation, and Air Conditioning
FEA	Finite Element Analysis
CDR	Cage Drone Robot
BOM	Bill of Materials
UK	United Kingdom

PID	Proportional-Integral-Derivative
MPC	Model-Predictive Control
mm	millimeter
m	meter
kg	kilogram

Table of contents

Appendices

Figures

Tables

1. Introduction

Tokamak reactors are leading scientific research in the field of nuclear fusion. This research contributes to the global efforts toward achieving clean and abundant energy for all. The complex process of fusion that allows tokamaks to generate large amounts of energy requires robust inspection and maintenance procedures inside the vacuum vessel component of the reactors. They are critical for ensuring that the reactor can be operated safely and effectively. However, the currently utilized traditional industrial robots struggle to navigate the narrow space inside the vacuum vessel. Therefore, a compact, lightweight, and protected structure intended for carrying out the inspection tasks will increase the safety and reliability of the nuclear reactors' inspection. This bachelor's thesis focuses on proposing a cage drone robot design that will fulfil the requirements posed by the environment of the tokamak fusion reactor and carry out inspection tasks inside its vacuum vessel component. The results of this thesis can be utilized to produce the first prototype of the cage drone robot and further test and refine its concept design for real inspection inside the tokamak reactor. Furthermore, the key results of this research could be applied beyond the nuclear industry, in particular, among sectors that also encounter extreme and challenging operational environments.

1.1. Background and motivation

Nuclear energy is one of the most prominent solutions for generating clean and abundant energy. The significance of scientific research in this field demands high reliability and efficiency of fusion reactors. Therefore, inspection and maintenance procedures are crucial for achieving the desired research and energy-generation goals without compromising the reactors' high levels of safety and operational efficiency. It becomes ever more important to develop a novel and autonomous structure that is compact and lightweight and, therefore, effective in carrying out inspection tasks.

1.2. Research problem and questions

The major inspection challenge encountered by the currently utilized industrial robots is the narrow and confined space of the vacuum vessel of the tokamak nuclear reactor. This thesis

focuses on proposing a concept design of a cage drone robot that will surpass this limitation. The research process is guided by the following questions:

- What are the key requirements for a robotic drone system design that operates inside the tokamak fusion reactor?
- How can the cage drone robot be designed to meet those requirements and overcome the limitations of traditional industrial robots?

These questions will establish a framework for the focus of the research and ensure its consistency.

1.3. Research methods

In order to answer the research questions, a combination of methods will be used. First, an extensive literature review will provide a context of the tokamak technology and the criticality of its inspection. The following in-depth review will assess the current robotic inspection systems and the application of drone robots for nuclear reactor inspection. These steps will formulate the essential design and functional requirements for the cage drone robot. Second, a 3D modelling tool, such as SolidWorks 3D CAD software, will be used to model the exterior and interior components of the cage drone robot. Lastly, the Finite Element Analysis tool of the SolidWorks environment will test the drones' airframe component to evaluate the suitability of the material selected. These methods will ensure a comprehensive proposal for the new cage drone robot design and, therefore, enhance the efficiency of the tokamak reactor inspection.

1.4. Scope of the research

The aim of this thesis is to propose a concept design of a compact, lightweight and protected cage drone structure to carry out inspection tasks inside the vacuum vessel of a tokamak reactor. This bachelor's thesis focuses on the size of the inspection drone as its only design requirement. The other aspects that could influence the drone's design, such as tokamaks' operating environment (temperature and radiation levels), lie beyond the scope and expertise of this research project and, therefore, are not considered.

1.5. Expected outcomes and significance

The expected output of this research includes a list of the functional and design requirements for the cage drone robot, CAD model and drawings of the resulting drone robot, its components, and a Finite Element analysis using the SolidWorks software. Additionally, this thesis aims to highlight areas for further design improvement to suit the extreme operating environment of the tokamak vacuum vessel - thereby having a greater impact on the realization of fusion energy as a viable and sustainable power source.

2. Literature Review

Tokamak reactors are paving the way for the research of fusion energy, offering a promising solution to sustainable and clean energy generation. The various fusion reactors like the International Thermonuclear Experimental Reactor (ITER), China Fusion Engineering Test Reactor (CFETR), and EU Demonstration Power Plant (DEMO) have, therefore, gained global recognition (Kikuchi and Azumi, 2015). However, ensuring the structural integrity of tokamak components, such as the vacuum vessel, under extreme conditions is challenging, requiring robust inspection procedures. Industrial robotic systems are often used for reactor inspection, but their large proportions limit their application. Moreover, it often causes the inspection needs of smaller fusion experiments to be overlooked (Mumgaard et al., 2014). Therefore, a compact and lightweight inspection solution is needed. The following preliminary review explores the history and structure of the tokamak reactor as well as the potential of unmanned aerial vehicles (UAVs), or drones, for inspection tasks within the tokamak vacuum vessel.

2.1. Historical background of tokamak reactors

Tokamak reactors have been developed to harness fusion energy and serve as a clean and abundant energy source. Since the Soviet Union's efforts to build the first reactor in the 1950s, the tokamak reactor concept was globally recognized as one of the most promising large-scale and emission-free sources of energy (Baker, Montgomery and Wilson, 1995). The progress of research in nuclear fusion has led to the development of various tokamak models. The joint efforts of various countries have created several models of fusion reactors, such as the ITER, CFETR, and the EU DEMO (Brown, 2018).

2.2. Tokamak reactor structure overview

Tokamak reactors are donut-shaped magnetic confinement devices designed to produce energy through fusion. The reaction occurs by confining hot plasma at high temperatures and pressures using strong magnetic fields. This process generates abundant energy without greenhouse emissions and minimal radiological waste (Creely *et al.*, 2020). According to Brown (2018), the main components of a tokamak reactor include:

- Cryostat: a confining environment for the vacuum vessel and the superconducting magnets.
- Magnets: a system of superconducting magnets that initiate and control reactor plasma.
- Vacuum Vessel: a torus-shaped, hermetically sealed vessel where the fusion reactions occur.
- Blanket: a module that covers and protects the vacuum vessel's inner walls from the fusion heat.
- Diverter: an element located at the bottom of the vacuum vessel that extracts heat produced by the fusion reaction.

Figure 1 illustrates the key inner components of a tokamak nuclear reactor. The presented cross-section of ITER tokamak includes the cryostat, vacuum vessel, blanket, and diverter components (Dubus, 2014).

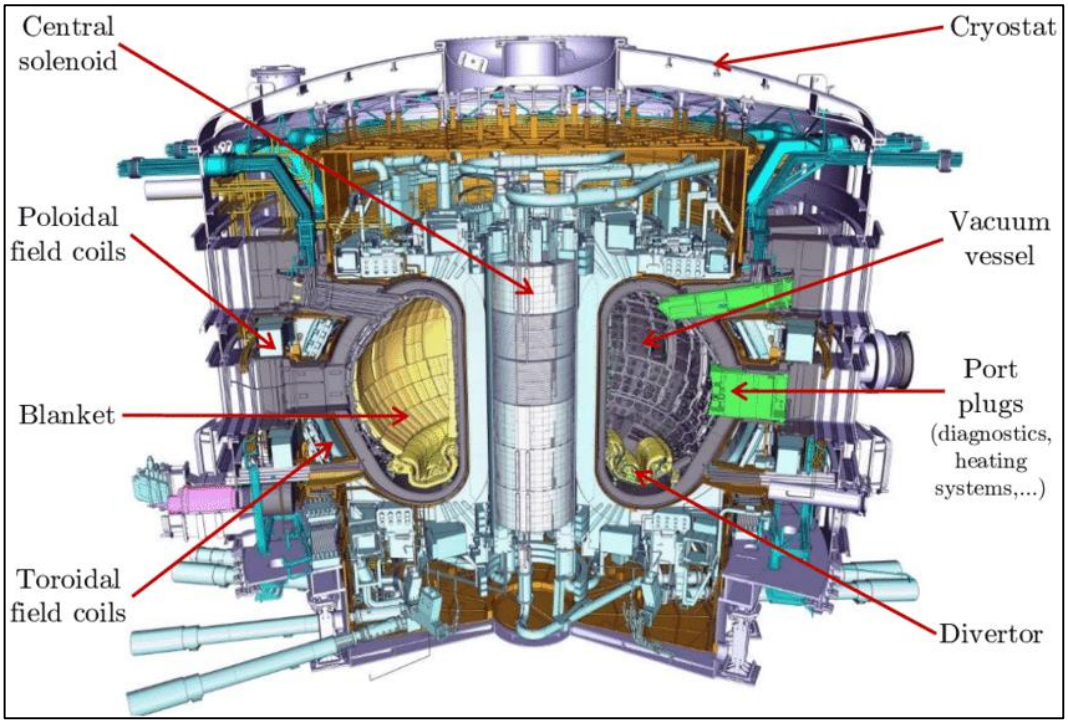


Figure 1: Main inner components of ITER tokamak. Source: Dubus, 2014.

2.3. Tokamak reactor inspection processes

Inspection processes are an important factor in tokamak fusion reactor operations. The high temperature and radiation levels that are characteristic of the fusion process require robustness of the reactor vessel components. Wang, Xu and Chen (2016) highlight that, in order to ensure the operational efficiency and reliability of tokamak reactors, inspection and maintenance are important. Consistent reactor inspection could, therefore, significantly improve the safety and prolong the lifetime of the reactor components.

2.4. Tokamak inspection systems

The inspection and maintenance of tokamaks highly depend on robotic and Remote Handling (RH) (Gargiulo et al., 2008). These operations take place inside the vacuum vessel of the reactor, thereby minimizing risks of human intervention. The world's largest fusion research project, ITER, demonstrates two main reasons to consider robotic and RH systems:

1. The extreme operational environment of the vacuum vessel: high vacuum, high temperature, and high radiation (Du et al., 2015).
2. The limited space inside the tokamak machine (ITER Organisation, 2024b).

These conditions have driven the development of different inspection systems globally, such as the French Atomic Energy Commission's (CEA) Articulated Inspection Arm (AIA) (Gargiulo et al., 2008), Chinese Academy of Science's flexible in-vessel inspection manipulator (FIVIS) (Peng et al., 2010), and MIT Plasma Science and Fusion Centre's inspection system (Mumgaard et al., 2014).

2.5. Drone robot applications

Large and complicated inspection systems are often unnecessary for medium or small-scale fusion experiments. However, occasional inspection of these types of reactors could still yield valuable data for scientific research (Mumgaard et al., 2014). Therefore, there may be demand for a compact and protected inspection system. Potential solutions may involve Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, as they are used in many modern industries. There are various forms, from consumer models to advanced military systems, and their typical functions include surveillance, agriculture, construction, and disaster management (Dekoulis, 2018). Their applicability to challenging operational environments and their adaptivity to structural changes make them suitable candidates for

carrying out inspection and maintenance tasks inside the vacuum vessel of tokamak fusion reactors.

3. Methods

The triangulation approach used to provide a framework for the cage drone robot design consists of three steps: in-depth literature review, use of the SolidWorks 3D modelling software, and the Finite Element Analysis. By combining these methods, this research will propose a new concept for the cage drone robot design. The reliability aspect will also be considered to ensure the validity of results.

3.1. Cage Drone Robot Design and Functional Requirement Determination

The literature review was important to establish an overview of the tokamak's operational environment. It collected information from trusted scientific papers, journals, and reports that will guide the cage drone robot design forward. It also provided the context of the tokamak technology and the criticality of the tokamak vacuum vessel inspection. This formed a base for the key design and functional requirements of the cage drone robot concept. The most important information gathered during the literature review method was the following:

- Key dimensional parameters of the blanket confinement and produced plasma volume in the three most prominent tokamak variants.
- Dimensions of the access ports of the tokamak vacuum vessel.
- Main functional and design requirements to be implemented in the cage drone design.

The literature review section is supplemented with an additional calculation step. It involves calculating the cross-section area A of the D-shaped vacuum vessel of the tokamak reactor. This parameter ensures that the produced design will be suitable for operating inside the reactor. It is calculated using a combination of the areas of a semicircle and a rectangle:

$$A = \frac{\pi R^2}{2} + 2a(R - a) \tag{1}$$

where A is the area of the cross-section [m^2], π is a mathematical constant [no unit], R is the major radius [m], and a is the minor radius [m].

The information obtained ensures that the proposed design is well-suited for carrying out inspection tasks inside the tokamak vacuum vessel.

3.2. 3D Modelling

The 3D modelling step aims to produce an accurate cage drone design representation, for which the 3D CAD Design Software is used. The SolidWorks software provides an equipped environment for cage drone model development, modification, and visualization. The process focuses on modelling individual components of the drone according to the design and functional requirements collected during the in-depth literature review. The modelling process has three steps: modelling of the drone exterior components, modelling of the drone interior components, and the final assembly production. To ensure a consistent outcome, each drone component is further described in relation to its function and placement.

3.2.1. Methodological approach to exterior drone components specification

The exterior unit of the drone design consists of four components. The components include Spider Base, Spider Top, Spider Arm, Fan and make up the airframe of the drone model. Each exterior component is assigned its own function.

- Spider base and spider top: The spider base serves as a foundational platform for the drone. It houses internal drone components and provides structural support. The spider top complements the spider base by enclosing the internal components of the drone and shielding internal components from environmental factors.
- Spider arm: The spider arm forms the structural framework of the drone by connecting the spider base to the spider top. There are four spider arms in total, which ensures the stability of the overall drone structure.
- Fan: The fan is an essential drone component that generates lift and propulsion to enable the drone's flight. The fans are placed on each of the four spider arms respectively.

Figure 2 illustrates the intended design of the exterior drone unit. The unit is referred to as the airframe assembly and includes the spider base, spider top, and spider arm components.

Figure 2: SolidWorks model of the drone airframe component.

3.2.2. Methodological approach to interior drone components specification

The interior unit of the drone design consists of eight components. The components include the Distribution Board, Spinner, Spacer, Electrical Connector, Pillar, Motor, Battery, Electrical Unit and make up the internal padding of the drone model. Each interior component is assigned its own function.

- Distribution board: The distribution board serves as a hub for drone power distribution. The power is distributed from the battery to other electronic components of the drone. The design utilizes two distribution boards between the spider top and spider base components.
- Spinner: The spinner is the rotating part of the motor assembly that houses the propeller shaft and the fan blades. The drone design incorporates four spinners for each of the four propellers.
- Spacer: The spacer separates drone components, such as the spider base and top, and helps maintain spacing and alignment. The drone design utilizes four spacer pieces.
- Electrical connector: The electrical connector connects different components of the drone. The model utilizes four electrical connectors on each spider arm's side.

- Pillar: The pillars are used to secure the interior drone components. The drone design includes four pillars below the motor units on the bottom of each spider arm.
- Motor: The motors are used to drive the drone propellers. Their rotational motion generates thrust and lifts the drone from the ground. The design utilizes four motor units on each spider arm's top.
- Battery: The battery serves as the primary power source for the drone. It is placed on top of the drone design.
- Electrical unit: The electrical units are responsible for controlling the electrical signals of the drone. The design utilizes two electrical units placed on top of the distribution board.

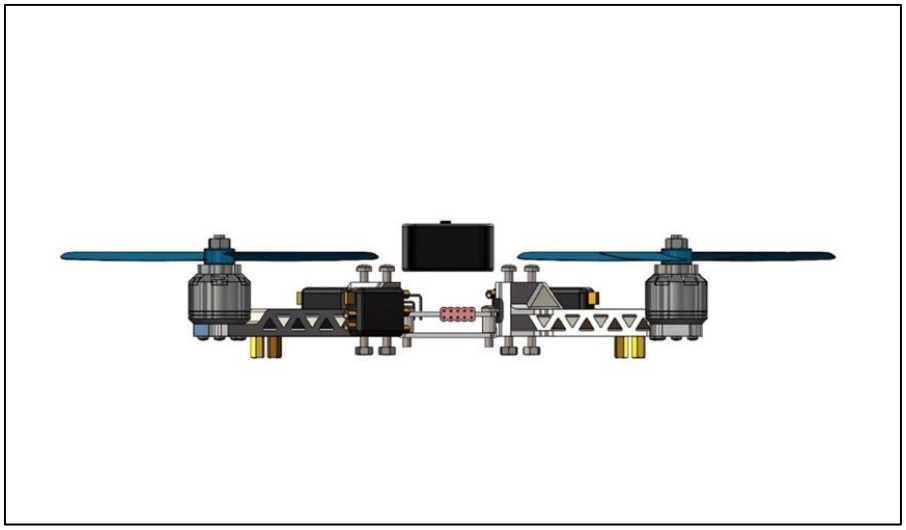


Figure 3: SolidWorks model of the interior drone components.

Figure 3 illustrates the interior unit of the drone design. The unit includes all the components mentioned above. The exterior components form the outer structural framework of the drone, while the interior components ensure the proper operation of the drone. The exterior and interior components are essential for ensuring the drone's functionality and performance.

3.2.1. Methodological approach to drone cage component specification

The confined space of the tokamak nuclear reactor poses operational challenges. The risk of a drone collision with the blanket modules of the ITER reactor is high. In such an

environment, it is necessary to ensure the safety of the drone with a protective structure such as a cage (Khalil *et al.*, 2024).

The cage around the drone protects it during inspection tasks. The cage allows the drone to navigate and operate effectively in challenging environments. Caged drones with similar operational requirements have already been designed for heating, ventilation, and air conditioning (HVAC) duct inspection. For example, rectangular-cage Passport (Edgerton *et al.*, 2019), spherical-cage Fleye (Borik *et al.*, 2019), and spherical-cage Hybrid Rolling (Khalil *et al.*, 2024) drones.

The design unitizes a spherical cage. The cage encapsulates the drone and provides passive protection and collision resistance. Figure 4 illustrates the profile of the cage. Including a cage unit in the design process enhances the drone's capabilities for safe and efficient operation by providing structural support and shielding the drone from collisions.

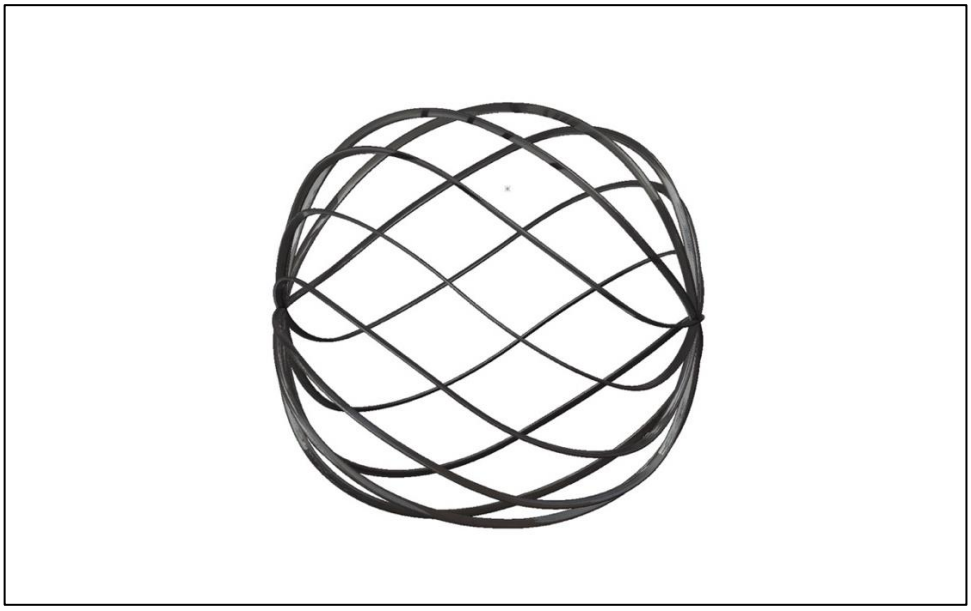


Figure 4: SolidWorks model of the drone cage.

3.3. Finite Element Analysis

The implementation of the Finite Element Analysis aims to analyze the structure's integrity under external stress conditions. The analysis includes the following steps: model definition, assignment of materials, assignment of constraints, meshing, and computation of the result. After creating the complete CAD model of the drone, the SolidWorks software will be used to perform the FEA static simulation.

In particular, the behavior of the airframe component of the drone will be simulated under external stress conditions of thrust generated by the propellers. The thrust will be represented as an external force of 18 N (eighteen newtons) applied upwards to each of the four spider arms. The spider base and the spider top components will be assigned a fully fixed constraint, preventing their movement due to the external force. The material for the airframe assembly will be defined as aluminum alloy, which is widely used in the aerospace industry (Materials UK, 2023). Table 1 summarizes the material properties applied to the airframe structure. The assignment of the airframe material allows to generate a mesh of the airframe model and to run the FEA simulation. The results of the simulation will be presented in the "Results and Analysis" section of the paper.

Table 1: Material properties of the Aluminum Alloy applied to the airframe assembly.

Property	Value	Unit
Shear Modulus	28000	N/mm^2
Mass Density	2800	kg/m^3
Tensile Strength	186.126	N/mm^2

Table 1 contains information that will be applied for the weight calculation of the resulting drone component. The weight calculation will be guided by the volume and density variables of the respective structures:

$$W = V * d \tag{2}$$

where W is the resulting weight [kg], V is the volume [m^3], and d is the density [kg/m^3].

3.4. Reliability aspect

The reliability of the results ensures that the research work can be verified and trusted by the scientific community. Therefore, it is important to address how each of the selected methods will be checked. The basis for the reliability checks is presented in Table 2.

Table 2: The reliability aspects of the selected methods.

Method	**Reliability aspect**
Literature review	The reliability of the literature sources is checked: paper ranking, author citation rating, trustworthiness of the database. Additionally, the date-relevance of the resource is checked, and the gathered information is compared to different sources.
3D Modelling	The designed models are checked for individual consistency and fit during the overall assembly construction.
Finite Element Analysis	The obtained results are evaluated in relation to material properties, variables settings, mesh quality, and solver settings.

By following the outlined reliability checks the utilized triangulation method will be reliable and therefore, trusted by the scientific community.

4. Results and Analysis

The following chapter is divided into subchapters respective to the methods used in this research. Namely: Literature Review, 3D Modelling, and Finite Element Analysis. Key findings are presented, and descriptive analysis is formulated in the context of the research goals at hand. Additional references are made to relevant literature sources that further enhance the reliability and validity of the research. Therefore, the results follow the outlined triangulation method of the study.

4.1. Literature review

As discussed in the preliminary literature review, various tokamak models exist, including ITER, CTETR, and EU DEMO reactors. In this regard, an overview of their characteristics and operating environments is key for establishing the design and functional requirements for the inspection drone. These requirements are derived from the critical specifications of the reactors, such as the plasma proportions, temperature, and radiation levels inside the vacuum vessel, along with the drone's inspection objectives (Du *et al.*, 2015).

4.1.1. Design requirements

The operational environment of the reactor dictates the size requirement for the inspection drone. The process of fusion happens in a toroidal, D-shaped vacuum vessel. The vessel's inner walls are covered in blanket modules, making up a uniform protective layer of the plasma-facing surface (Song *et al.*, 2014). These blanket modules form the operating environment of the inspection drone. Table 1 summarizes the key dimensional parameters of the blanket confinement and produced plasma volume in three tokamak variants.

Table 3: Key parameters of the CFETR, ITER, and EU DEMO reactors.

Parameter	CFETR	ITER	EU DEMO
Major radius, R (m)	7.2 [a]	6.2 [b]	7.5 [c]
Minor radius, a (m)	2.2 [a]	2.0 [b]	2.9 [c]
Cross-section area, A (m^2)	62.96	47.09	71.02

Plasma volume, V (m^3)	1249 [a]	840 [b]	2217 [c]

Note. Data is from Liu *et al.* (2020)[a], ITER Organisation (2024)[b], and Federici *et al.* (2017)[c].

The obtained parameters serve as constraints for the size of the inspection drone. The available operational environment of the ITER design is the smallest compared to the CFETR and EU DEMO variants. Therefore, specifications of the ITER reactor are selected as major constraints, allowing for the resulting drone design to be used in bigger vacuum vessels.

Additional consideration should be given to the available access ports of the ITER vacuum vessel. There are forty-four access ports implemented in the ITER design. They include eighteen upper ports, seventeen equatorial ports, and nine lower ports for the entry of auxiliary systems for diagnostics, maintenance and other necessary operations (Moon *et al.*, 2023). The equatorial ports are prominently used for in-vessel inspection and maintenance tasks by the Porteur Articule´ en Cellule (PAC) manipulator and the Articulated Inspection Arm (AIA) (Chen and Cao, 2014). The dimensions of the ports are approximately 2 meters high and 2 meters deep, allowing for the effective operation of external inspection systems (Balshaw *et al.*, 2009).

4.1.2. Functional requirements

The functional requirements must ensure that the drone can effectively perform its inspection tasks while meeting the operational standards of the tokamak reactor vacuum vessel environment:

- Inspection capabilities: inspect the possible damage of the plasma-facing components of the vacuum vessel.
- Dimensional constraints: follow the size limitations of the vacuum vessel, not causing additional damage.
- Weight limitations: meet a maximum weight limit to ensure effective operation.
- Navigation and maneuverability: navigate and maneuver within the area inside the vacuum vessel.
- Remote operation: operate remotely, allowing for keeping a safe distance from the vacuum vessel.

- Battery life: have sufficient battery capacity to support the inspection missions.
- Additional features: possibility of employing commercial mechanical/electrical components and utilizing cage protection to mitigate damage resulting from possible collisions with the reactor vessel walls.

The outlined requirements serve as a basis for the key criteria of the inspection drone design. Most importantly, the scope of this research considers the inspection capabilities and dimensional constraints as the primary functional requirements of the drone, with the possibility for adding more features to ensure its functionality inside the ITERs' vacuum vessel environment.

4.1.3. Cage drone robot concept proposal

The overview of the unique operating environment of the ITER tokamak vacuum vessel has set specific constraints on the drone design proposal. Table 4 summarizes the main functional and design requirements implemented in the inspection drone design.

Table 4: Cage drone robot requirements summary.

Index	Name	Description
1	Capabilities	The drone shall be operated to inspect the plasma-facing components of the vacuum vessel inside the ITER fusion reactor.
2	Dimensions	The drone shall be designed to fit through the inspection ports (2 meters high, 2 meters deep) and operate within the ITER fusion reactor's cross-sectional area (47.09 square meters).
3	Weight	The drone shall not exceed the weight limit of a typical inspection drone (maximum 10 kilograms).
4	Additional features	The drone could implement additional protection features, such as cage confinement, to mitigate mechanical damage in case of collisions.

The outlined requirements guide the development of the inspection drone design. The main factors are drones' compactness, lightweight design, and shielding capabilities. By obeying these specifications, the inspection drone overcomes the limitations of traditional inspection robots and successfully meets the inspection needs of fusion reactors.

4.2. 3D Modelling

The final drone design combines all the individually designed components. The components are assembled into a complete model using a bottom-up approach. The resulting assembly is represented as a CAD model and a CAD drawing and is further complemented with a Finite Element Analysis (FEA) of the airframe assembly. The CAD models and corresponding drawings of the individual drone components are attached in Appendix 1 and 2 sections of the paper.

4.2.1. Cage Drone Robot CAD Model

The final CAD model assembly combines the drone's interior, exterior, and cage components. The model in Figure 5 and Figure 6 illustrates the geometrical relationship between the drone and the cage using the front and top views, emphasizing the drone's flying capability and the protective structure around it.

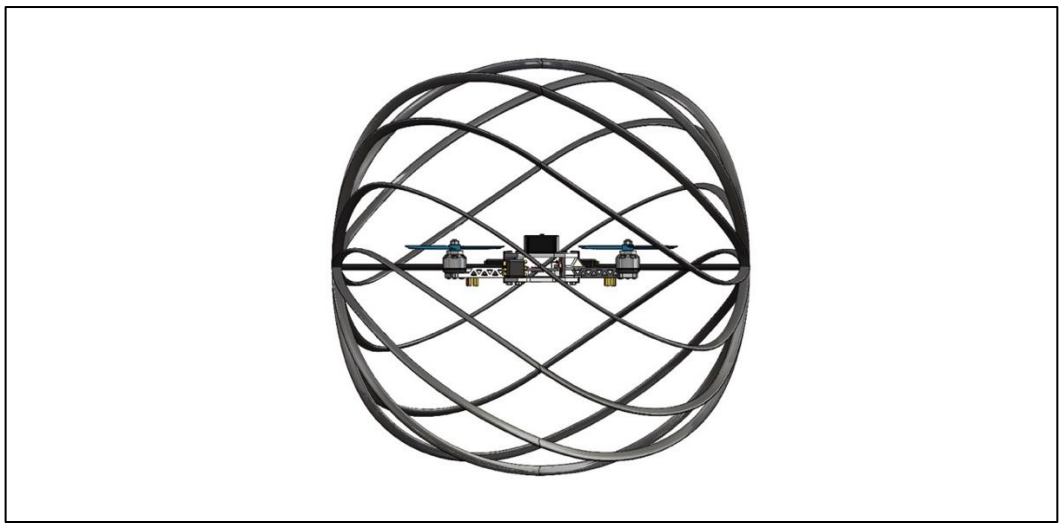


Figure 5: SolidWorks model of the cage drone assembly. Front view.

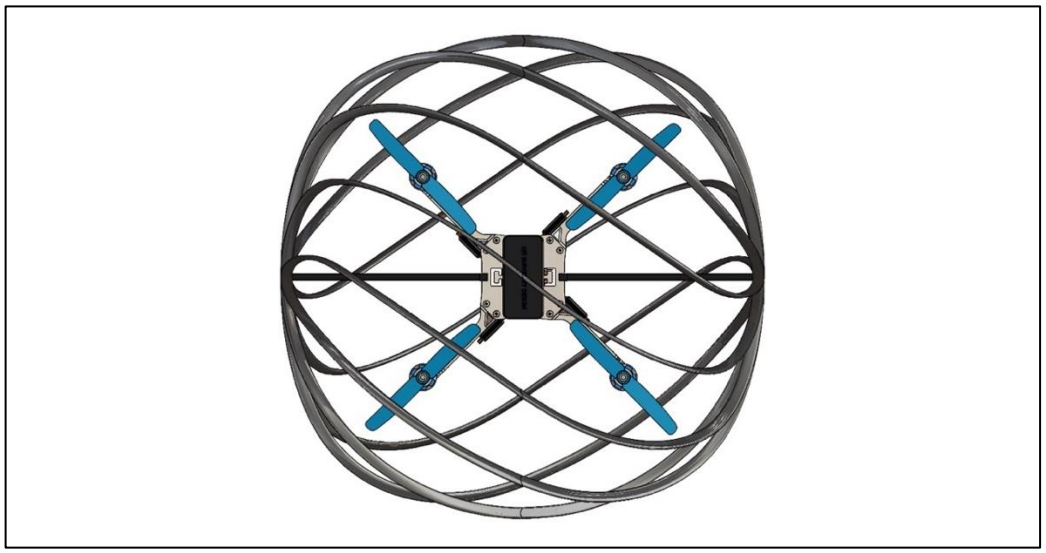


Figure 6: SolidWorks model of the cage drone assembly. Top view.

The cage is connected to the drone via two connecting rods attached to both sides of the sphere and the airframe, respectively. The rods provide structural support, ensuring the control and stability of the drone inside the cage. The CAD models of the corresponding components of the cage drone robot are attached in the Appendix 1 section of the paper.

4.2.2. Cage Drone Robot CAD Drawing

The CAD drawing in Figure 7 provides an overview of the cage drone assembly and its structural components. Each assembly component with a unique identification sequence is assigned to four main groups (CDR-001, CDR-002, CDR-003, and CDR-004). The sequence is applied to each sub-assembly of the main structure (e.g. CDR-001-001 for the spider base component or CDR-002-005 for the distribution board component). Further details on the identification groups of the cage drone robot components can be found in Appendix 4.

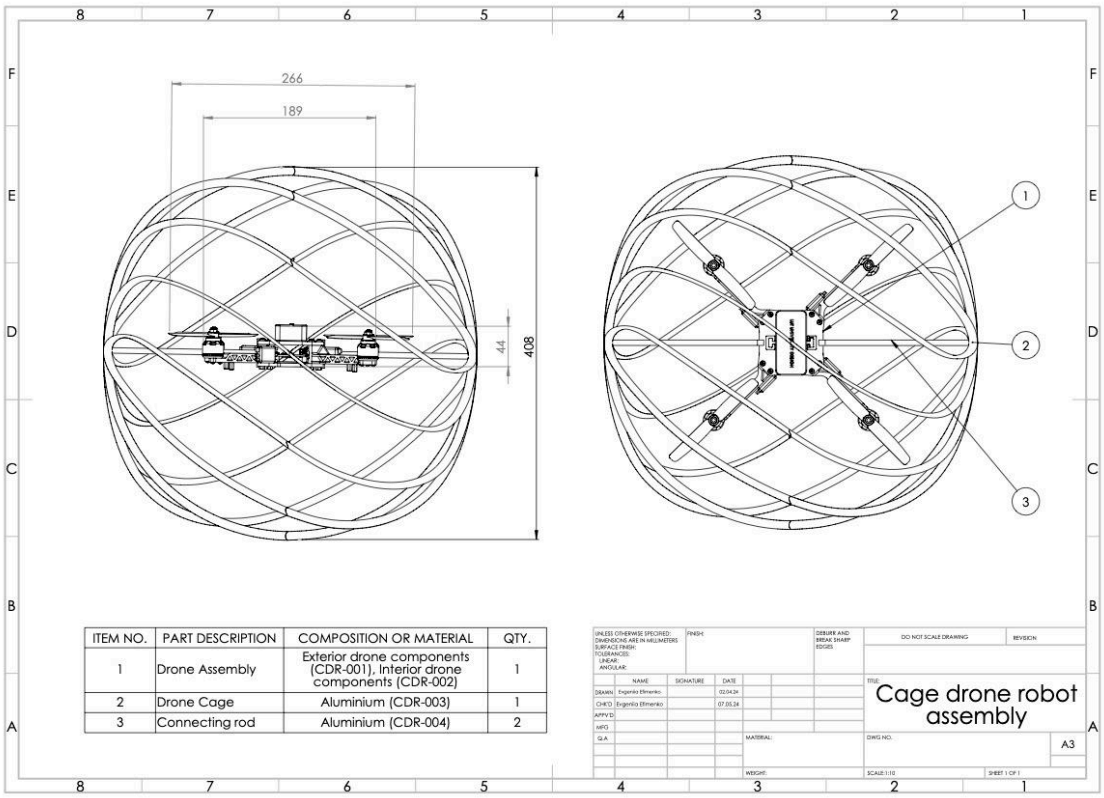


Figure 7: SolidWorks drawing of the cage drone robot assembly.

The drawing includes the overall dimensions, Bill of Materials (BOM) with the corresponding subassemblies, and an information sheet for more detailed documentation. The overall dimensions of the technical drawings include the drone (266 by 44 millimeters) and the protective cage (400 by 400 millimeters) around it, which successfully meet the established dimensional requirements. The CAD drawings of the subassemblies and the individual components of the cage drone robot are attached in the Appendix 2 section of the paper.

4.3. Finite Element Analysis

The completed CAD model of the drone allowed the FEA static simulation to be performed using the SolidWorks software. The simulation analyzed the behavior of the airframe component under thrust generated by the fans. The external force of 18 N (eighteen newtons) was applied upwards to each of the four spider arms. The simulation plotted the results of the airframe displacement (Figure 8) and the static nodal stress (Figure 9).

Figure 8: Displacement of the airframe assembly under applied external force.

Figure 9: Static nodal stress within the airframe assembly under applied external force.

The resulting plots are supplemented with color scale bars on the right-hand side of the images. A detailed representation of the resulting plots can be found in Appendix 3 section of the paper. The key results of the FEA simulation are summarized in Table 5.

Table 5: Resulting values for the deformation and stress of the airframe assembly.

Property	Value	Unit
Maximum Deformation	7.139e-05	m
Maximum Stress	3.081e-02	N/m^2

The obtained plots and numerical results of the simulation provide insights into the mechanical behavior of the airframe assembly. The applied external force conditions, such as thrust generated by the motors, allow for the accurate representation of drone operation when completing the nuclear reactor inspection tasks.

4.3.1. Analysis of the selected material

The results obtained from the Finite Element Analysis imply that the selected material of aluminum alloy 2024 would withstand the external thrust force, meaning that there would not be any compromise between the durability and the material's weight. Therefore, it is possible to make an estimation of the weight of the cage drone robot based on the selected material. The overall dimensions of the drone (266 by 44 mm) and the aluminum alloy 2024 suggest that the drone unit weighs 1.4 kg. Considering the weight of the specified electronic components, the estimation reaches 1.5 kg. Furthermore, the nylon spherical cage has highly lightweight properties (0.004 kg for the 400 by 400 mm dimensions) and therefore does not contribute to the overall weight significantly.

In summary, the finite element analysis provided a good foundation for the weight estimation of the resulting cage drone robot design. With an overall weight of 1.5 kilograms, the cage drone robot meets the weight requirements for successful inspection inside the tokamak reactor.

5. Discussion

The following discussion chapter provides an in-depth reflection of the design process, the implications of the resulting design, and its limitations, ending with several recommendations for future design improvement.

5.1. Design process interpretation

The tokamak fusion reactor's operational environment dictated the drone's design process. The limited space, high temperature, and extreme radiation levels of the tokamak vacuum vessel were outlined as the key reasons for implementing robotic inspection systems (Maisonnier, 2001). The benefits of intermediate inspection during small-scale fusion experiments further supported the cage drone design proposal.

A concrete definition of a drone's workspace was an important step in the design process. Among different tokamak configurations, such as CFETR, ITER, and EU DEMO, the ITER reactor was selected for its active research phase and the possibility of scaling the dimensions of the proposed design for bigger environments. The geometry of the inspection ports of ITER has set additional limits to the dimensions of the drone robot.

The following steps aimed at fulfilling the robots' functional and design requirements. After considering the overall dimensions, the drone and cage components were modeled separately. The drone assembly followed a conventional design scheme of multi-rotor drones with four propellers generating thrust that lifts the drone body. The selected four-propeller configuration would also guarantee the stability and maneuverability of the drone robot (Ji, Ma and Sam Ge, 2020). The cage assembly has a spherical profile of S-shaped lines to account for future design development. For example, the curvature of separate elements would allow the cage to fold around its central axis, introducing a more flexible and versatile design profile.

The Finite Element Analysis provided more insights into drones' structural characteristics — the analysis aimed at ensuring the durability of the airframe elements. In particular, the static analysis of the spider arms deformation showed an acceptable result of 7.139e-05 meters, meaning that the uplift force generated by propellers will not cause irreversible damage to the drones' structure. The material selected for the airframe was an aluminum

alloy 2024, which displays good fatigue, strength, and weight properties best suited for aircraft structures (Smiths Metal Centres, 2023).

5.2. Implications of the resulting design

A combination of Literature Review, 3D modelling, and Finite Element Analysis methods allowed for a complete design of the cage drone robot. The resulting design fulfils the key functional requirements: its overall dimensions of 400 by 400 millimeters are fit for the ITER inspection ports, and the aluminum and copper-based materials ensure the lightweight structure of 1.5 kilograms such that the overall design is well-suited for remotely carrying out inspection tasks inside the ITER vacuum vessel.

However, several considerations should be made before using the design for production. Prototyping and testing procedures are necessary to ensure the integrity of the proposed design. In particular, the prototype could utilize additive manufacturing techniques, such as 3D printing, for rapid prototyping. This procedure would allow for refining, iterating, and reviewing the robots' design features, which could lead to overall performance optimization. For example, the length of the spider arms, spacing between the top and bottom plates, placement of the battery and other critical components.

Furthermore, the material suggested in the final design could be altered depending on the available time and resources. Materials such as aluminum and copper-based alloys could be more demanding to build prototypes with due to longer machining times for metals compared to additive manufacturing times for plastic filaments. An additional remark regarding the final material selection is made in the "Design limitations" section of the paper.

5.3. Design limitations

The proposed cage drone robot design has several important limitations. The design does not consider the high radiation and temperature levels inside the tokamak vacuum vessel. Although these characteristics lie beyond the expertise of this research project, it is worth acknowledging that they heavily affect the material selection for the final cage drone structure. The suggested aluminum alloy 2024 is a well-suited selection for normal environmental conditions but does not apply to the actual operational environment of the vacuum vessel.

Furthermore, the design does not include a detailed description of the electrical components of the robot. The CAD model includes necessary drone components such as the battery, motors, connectors, and a distribution board. However, their interconnection through an electrical control system was not the focus of the design process. The design is, therefore, open to the implementation of different control systems, such as proportional-integral-derivative (PID), model-predictive (MPC), or adaptive controllers (Bolton, 2002).

Finally, the design did not consider the visual inspection component of the drone. However, the ongoing research in inspection technologies presents a wide range of options. There is a possibility of implementing high-definition cameras and fiber-optical or laser scanning systems, depending on the set objectives for the tokamak inspection (Maisonnier, 2001).

In summary, the limitations of the current design include material selection, electrical control system design, and visual inspection tools. These aspects could, therefore, be developed in future iterations of the cage drone robot design.

5.4. Further recommendations

The proposed cage drone robot design has several points for improvement. In addition to the listed limitations, the design could benefit from making the following considerations:

- Prioritize materials capable of withstanding high temperature and radiation levels. The proposed aluminum alloy 2024 could be replaced with radiation-resistant alloys, such as the tungsten-based high entropy alloy.
- Integrate electrical systems for continuous drone control. The current model design does not include control systems for sensor data evaluation. The possibility of integrating the proportional-integral-derivative (PID), model-predictive control (MPC), or adaptive controllers could be researched further.
- Evaluate visual inspection tools suitable for the tokamak environment. The commonly used solutions used by inspection systems include fiber-optical systems and laser scanning technologies.
- Develop the design and functionality of the protective cage component. The current design profile could be enhanced in relation to its foldability and impact-resistance aspects, which are important for the overall functionality of the proposed drone robot design.

6. Summary

This bachelor's thesis proposed a cage drone robot design that addresses the limitations of traditional industrial robots in the inspection of tokamak fusion reactors. The primary objective was to design a compact, lightweight, and protected cage drone robot for the remote inspection of the tokamak vacuum vessel. The objective was guided by two research questions concerning the drone requirements and key steps towards their achievement.

The objective was reached by utilizing the triangulation method, which consisted of Literature Review, 3D modelling, and Finite Element Analysis. The literature review step assessed the tokamak vacuum vessel environment and formed key design and functional requirements of the cage drone robot. The 3D modelling process resulted in a detailed virtual representation of the final drone design and its components, supplemented by technical drawings. The finite element analysis was conducted to evaluate the performance of the selected material under external stress conditions. Furthermore, the reliability aspect of the respective methods was ensured during each of the research phases.

The thesis further acknowledged the limitations of the proposed design. The design did not account for the high radiation and temperature levels inside the tokamak vacuum vessel, which otherwise would significantly impact the proposed concept. Additionally, the electrical control system and visual inspection tools were not addressed, leaving room for further improvement.

Recommendations for further design development include assessing other materials capable of withstanding extreme environments of the vacuum vessel, enhancing the design profile of the protective cage structure, along with integrating control systems and visual inspection tools to ensure suitability of future design iterations for operations inside the tokamak fusion reactor.

The continuation of research in this area will have a significant contribution towards maintaining operational efficiency and the overall reliability of the tokamak fusion reactors, thereby supporting realization of fusion energy as a viable and sustainable power source.

References

Baker, C.C., Montgomery, B. and Wilson, K.L. (1995) 'ITER-a world class challenge and opportunity', *IEEE Transactions on Appiled Superconductivity*, 5(2), pp. 61–68. Available at: https://doi.org/10.1109/77.402509.

Balshaw, N.H. *et al.* (2009) 'ITER Diagnostic Port Plug Design', *Fusion Science and Technology*, 56(2), pp. 661–665. Available at: https://doi.org/10.13182/FST09-A8984.

Bolton, W. (2002) *Control systems*. Oxford: Newnes.

Borik, A. *et al.* (2019) 'Caged Quadrotor Drone for Inspection of Central HVAC Ducts', in *2019 Advances in Science and Engineering Technology International Conferences (ASET)*, Dubai, United Arab Emirates: IEEE, pp. 1–7. Available at: https://doi.org/10.1109/ICASET.2019.8714539.

Brown, T.G. (2018) 'Three Confinement Systems—Spherical Tokamak, Standard Tokamak, and Stellarator: A Comparison of Key Component Cost Elements', *IEEE Transactions on Plasma Science*, 46(6), pp. 2216–2230. Available at: https://doi.org/10.1109/TPS.2018.2832457.

Chen, P. and Cao, Q. (2014) 'Development of a Remote Handling Robot for the Maintenance of an ITER-Like D-Shaped Vessel', *Science and Technology of Nuclear Installations*, 2014, pp. 1–9. Available at: https://doi.org/10.1155/2014/526520.

Creely, A.J. *et al.* (2020) 'Overview of the SPARC tokamak', *Journal of Plasma Physics*, 86(5), p. 865860502. Available at: https://doi.org/10.1017/S0022377820001257.

Dekoulis, G. (ed.) (2018) *Drones - Applications*. InTech. Available at: https://doi.org/10.5772/intechopen.70910.

Du, L. *et al.* (2015) 'A new trial of tokamak in-vessel inspection manipulator', *Fusion Engineering and Design*, 98–99, pp. 1701–1705. Available at: https://doi.org/10.1016/j.fusengdes.2015.06.164.

Dubus, G. (2014) *From Plain Visualisation to Vibration Sensing: Using a Camera to Control the Flexibilities in the ITER Remote Handling Equipment (Doctoral Dissertation)*.

Edgerton, K. *et al.* (2019) 'Numerical and experimental comparative performance analysis of emerging spherical-caged drones', *Aerospace Science and Technology*, 95, p. 105512. Available at: https://doi.org/10.1016/j.ast.2019.105512.

Federici, G. *et al.* (2017) 'European DEMO design strategy and consequences for materials', *Nuclear Fusion*, 57(9), p. 092002. Available at: https://doi.org/10.1088/1741-4326/57/9/092002.

Gargiulo, L. *et al.* (2008) 'Development of an ITER relevant inspection robot', *Fusion Engineering and Design*, 83(10–12), pp. 1833–1836. Available at: https://doi.org/10.1016/j.fusengdes.2008.06.039.

ITER Organisation (2024a) *ITER Facts & Figures*, *ITER*. Available at: http://www.iter.org/factsfigures (Accessed: 29 February 2024).

ITER Organisation (2024b) *What is a Tokamak*, *ITER*. Available at: http://www.iter.org/mach/tokamak (Accessed: 17 February 2024).

Ji, R., Ma, J. and Sam Ge, S. (2020) 'Modeling and Control of a Tilting Quadcopter', *IEEE Transactions on Aerospace and Electronic Systems*, 56(4), pp. 2823–2834. Available at: https://doi.org/10.1109/TAES.2019.2955525.

Khalil, A. *et al.* (2024) 'Autonomous Control of a Hybrid Rolling and Flying Caged Drone for Leak Detection in HVAC Ducts', *IEEE/ASME Transactions on Mechatronics*, 29(1), pp. 366–378. Available at: https://doi.org/10.1109/TMECH.2023.3279870.

Kikuchi, M. and Azumi, M. (2015) *Frontiers in fusion research II: introduction to modern Tokamak physics*. Cham: Springer.

Liu, Xiaogang *et al.* (2020) 'Progress in the conceptual design of the CFETR toroidal field coil with rectangular conductors', *Nuclear Fusion*, 60(4), p. 046032. Available at: https://doi.org/10.1088/1741-4326/ab742d.

Maisonnier, D. (2001) 'Viewing and inspection in tokamak machines', *Fusion Engineering and Design*, 56–57, pp. 135–144. Available at: https://doi.org/10.1016/S0920-3796(01)00601-9.

Materials UK (2023) *Aerospace Grade Aluminum*, *Materials UK*. Available at: https://www.thyssenkrupp-materials.co.uk/aerospace-grade-aluminum (Accessed: 29 March 2024).

Moon, H. *et al.* (2023) 'Evaluation of the functional acceptability of the ITER vacuum vessel', *Nuclear Fusion*, 63(1), p. 016003. Available at: https://doi.org/10.1088/1741-4326/aca1d0.

Mumgaard, R.T. *et al.* (2014) 'A small, novel, remote in-vessel inspection system for the Alcator C-Mod tokamak', *Fusion Engineering and Design*, 89(11), pp. 2784–2788. Available at: https://doi.org/10.1016/j.fusengdes.2014.08.003.

Peng, X.B. *et al.* (2010) 'Conceptual design of EAST flexible in-vessel inspection system', *Fusion Engineering and Design*, 85(7–9), pp. 1362–1365. Available at: https://doi.org/10.1016/j.fusengdes.2010.03.043.

Smiths Metal Centres (2023) '2024 Aluminium Technical Datasheet'. Available at: https://www.smithmetal.com/pdf/aluminium/2xxx/2024.pdf.

Song, Y. *et al.* (2014) 'Concept design on RH maintenance of CFETR Tokamak reactor', *Fusion Engineering and Design*, 89(9–10), pp. 2331–2335. Available at: https://doi.org/10.1016/j.fusengdes.2014.03.045.

Wang, H., Xu, L. and Chen, W. (2016) 'Design and implementation of visual inspection system handed in tokamak flexible in-vessel robot', *Fusion Engineering and Design*, 106, pp. 21–28. Available at: https://doi.org/10.1016/j.fusengdes.2016.03.005.

Appendix 1. CAD Models of the Cage Drone Robot Assembly and Components

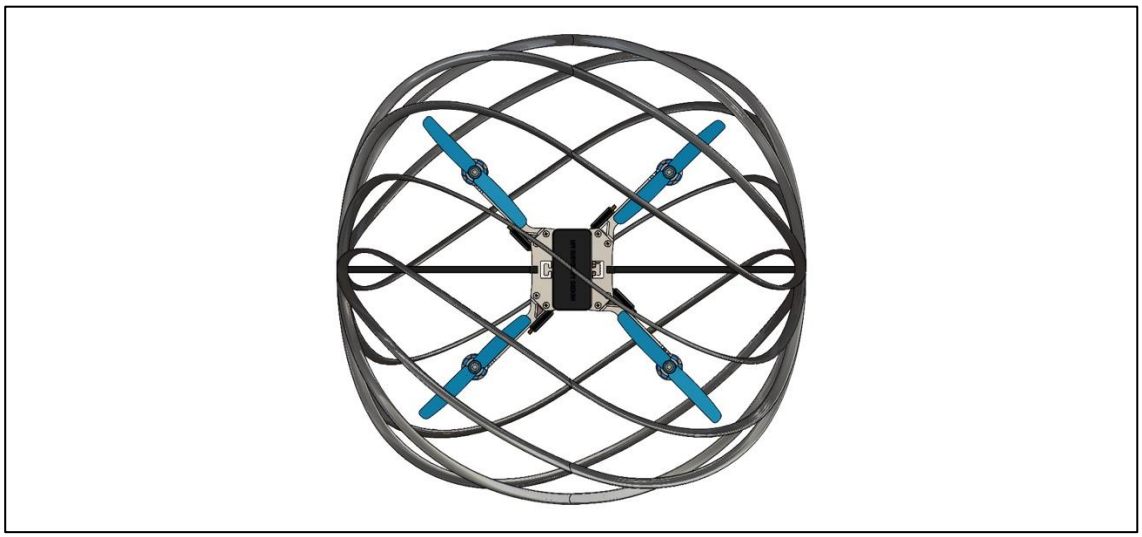


Figure 10: SOLIDWORKS model of the cage drone assembly. Top view.

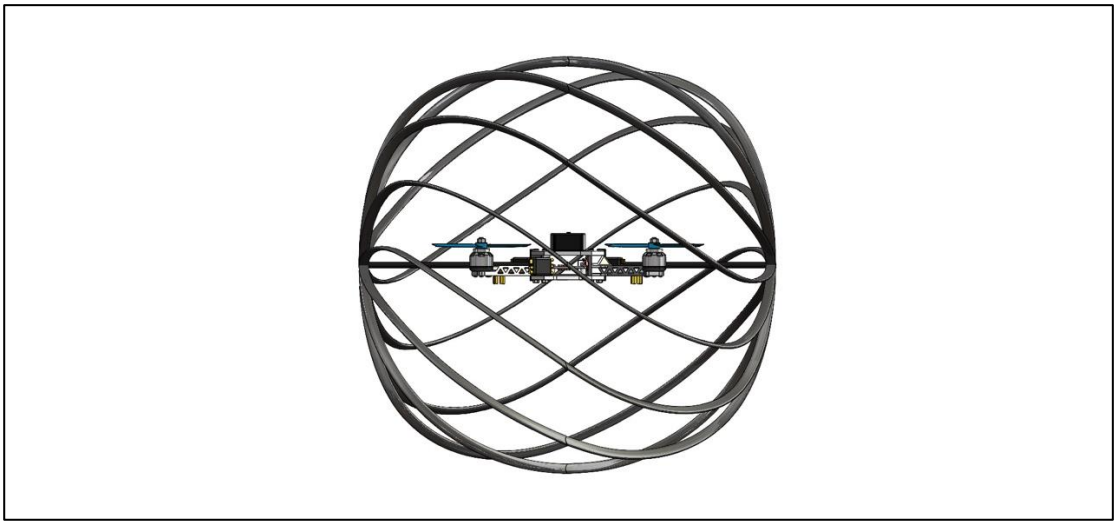


Figure 11: SOLIDWORKS model of the cage drone assembly. Front view.

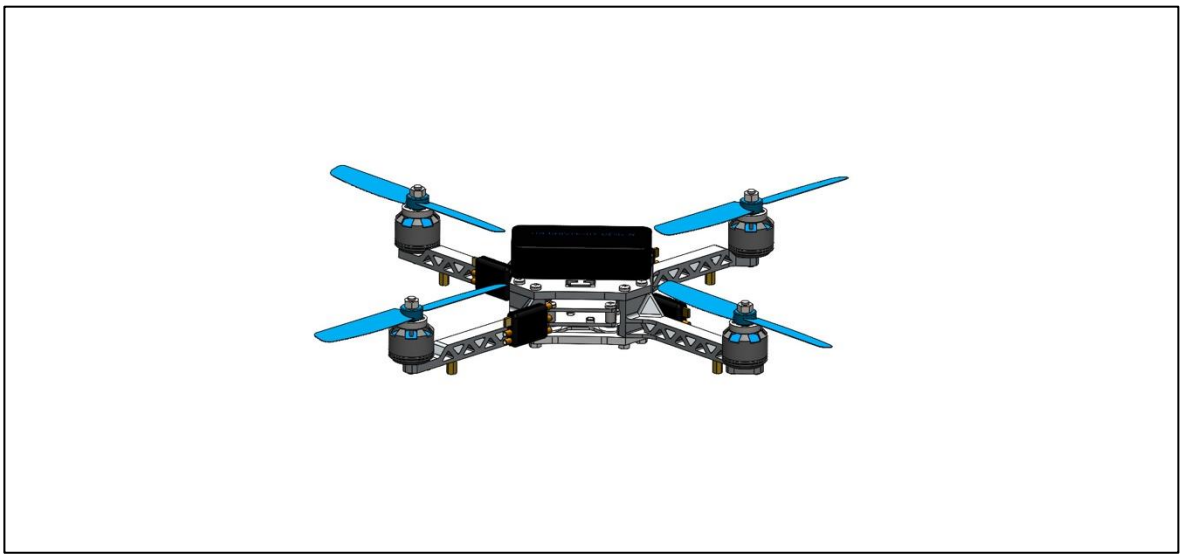


Figure 12: SOLIDWORKS model of the drone assembly.

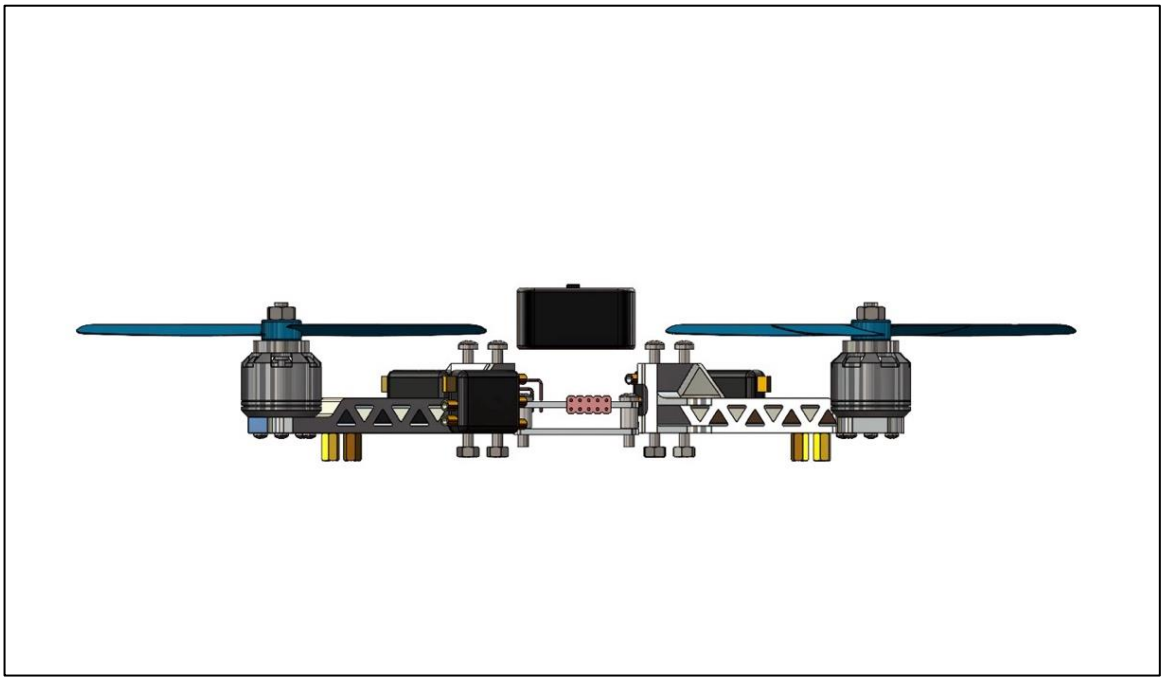


Figure 13: SOLIDWORKS model of the interior drone components.

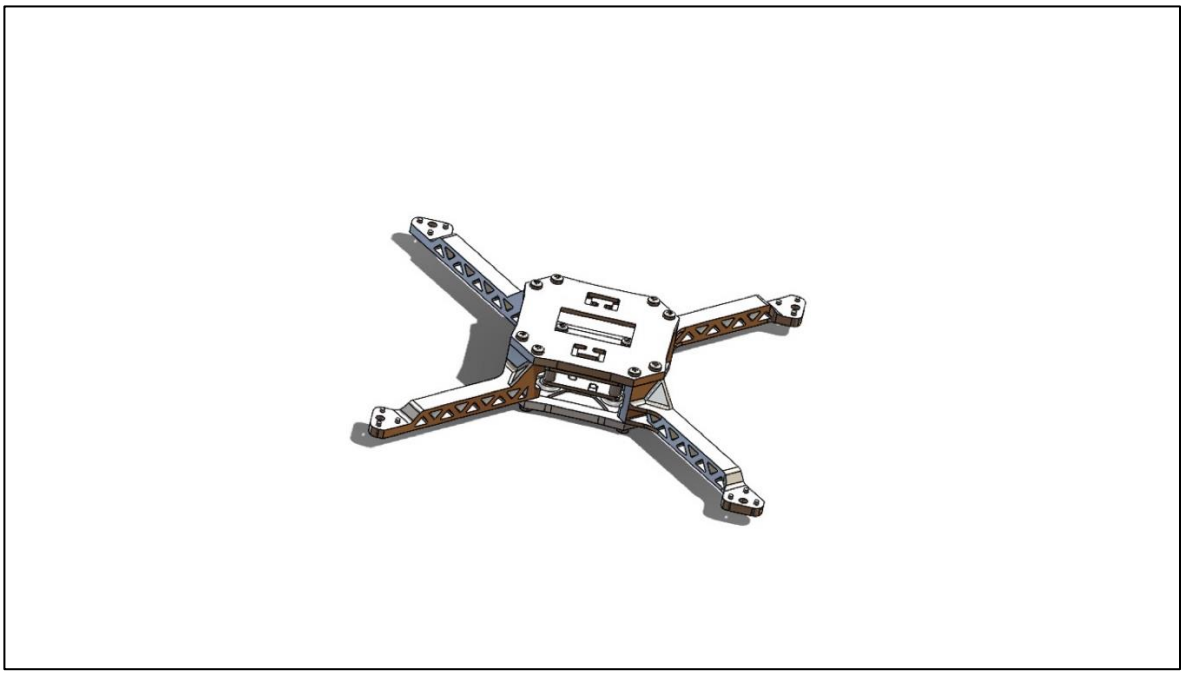


Figure 14: SOLIDWORKS model of the drone airframe component.

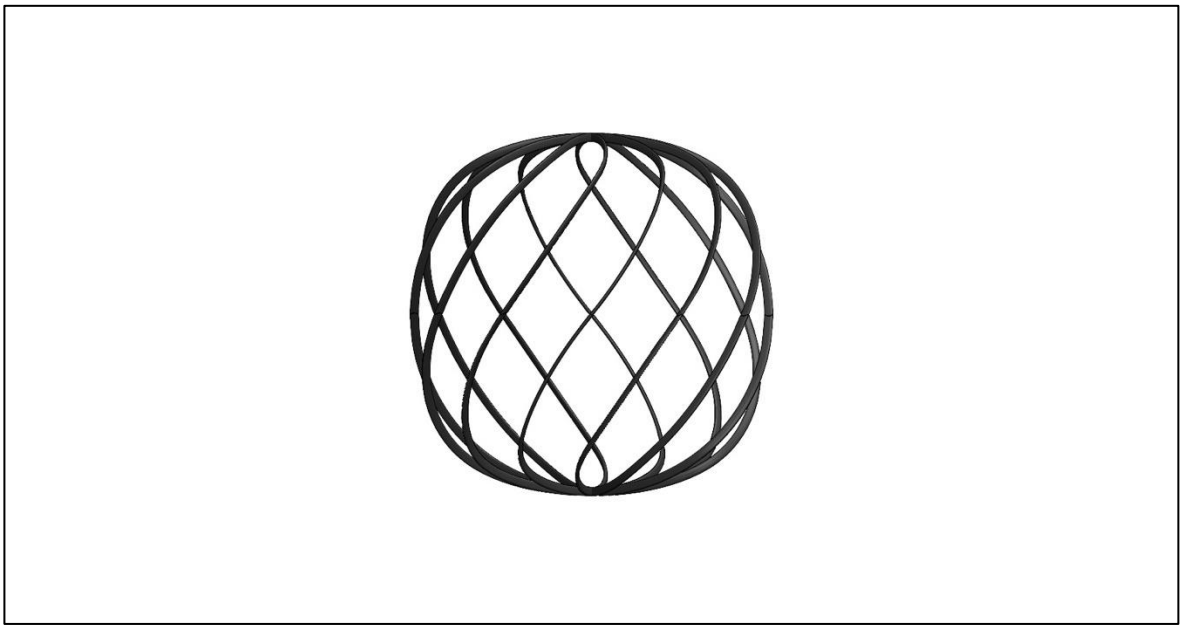


Figure 15: SOLIDWORKS model of the drone cage unit.

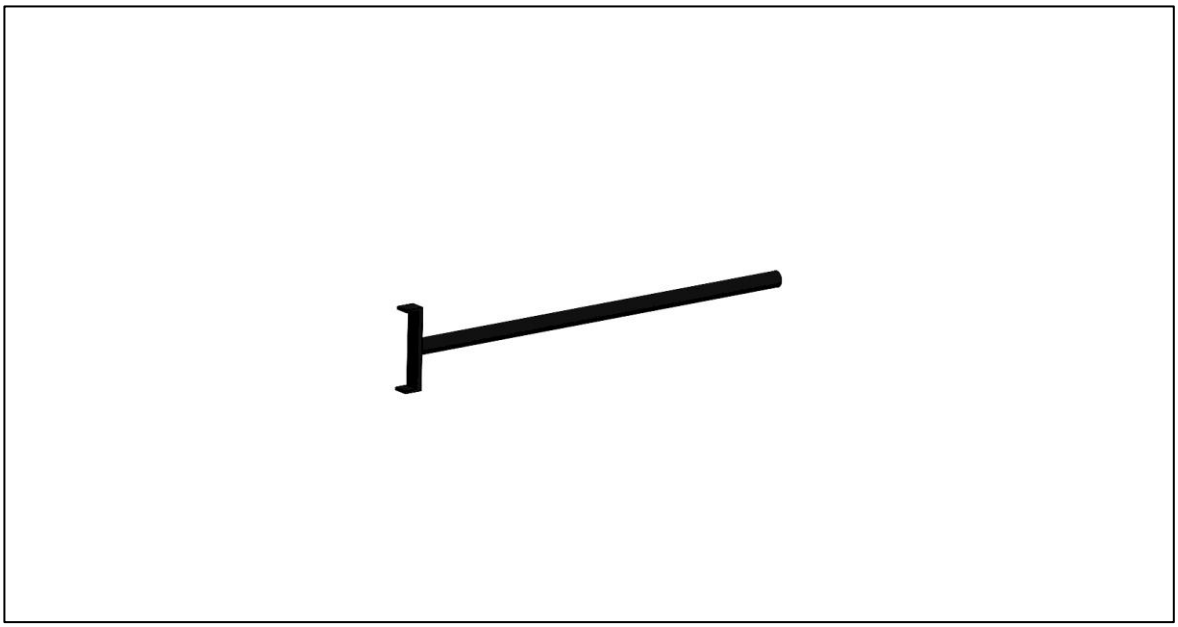


Figure 16: SOLIDWORKS model of the connecting rod component.

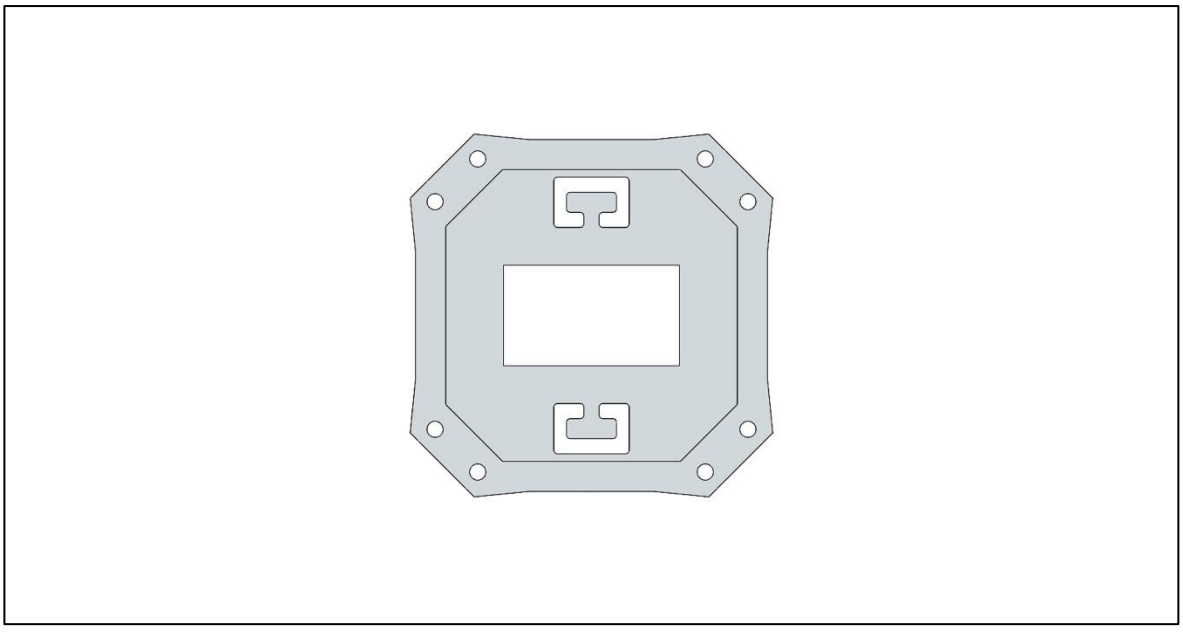


Figure 17: SOLIDWORKS model of the spider top component.

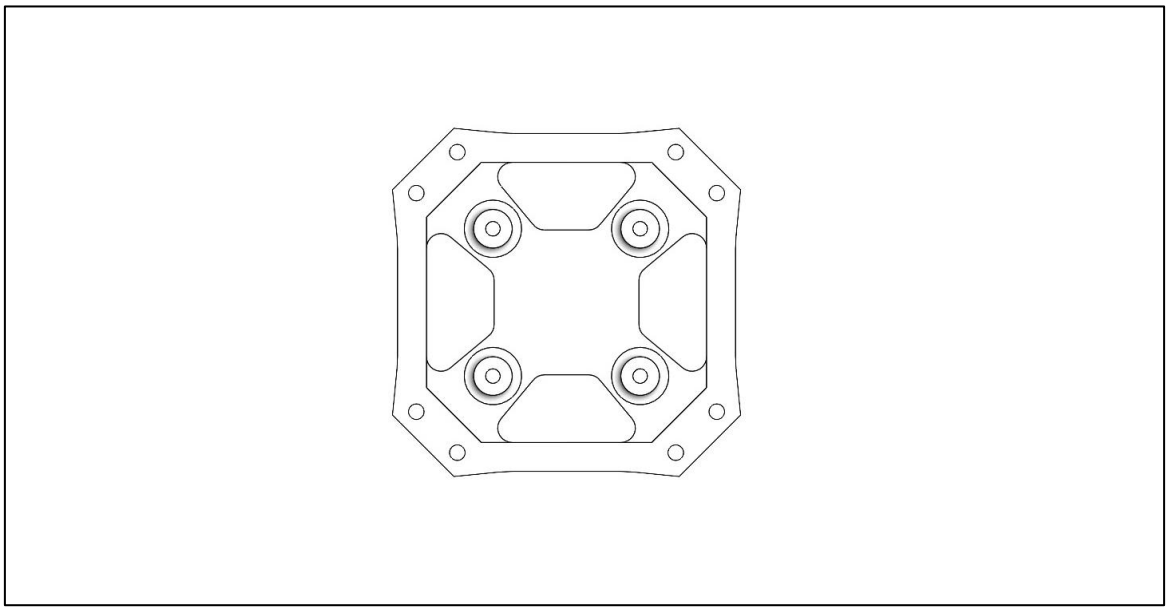


Figure 18: SOLIDWORKS model of the spider base component.

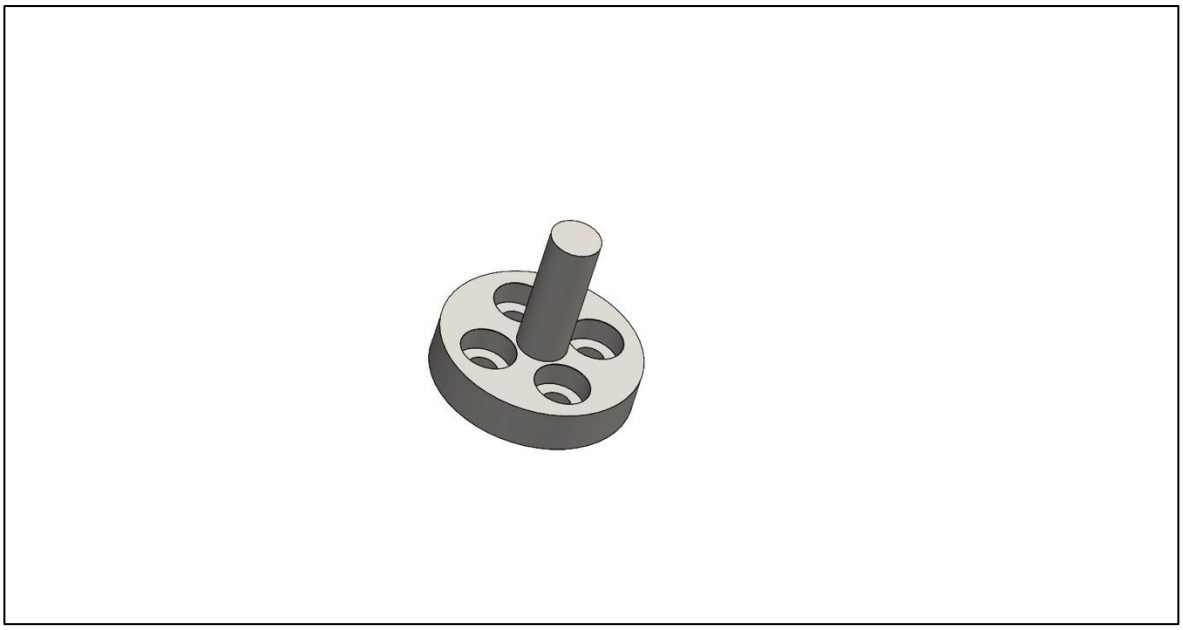


Figure 19: SOLIDWORKS model of the spinner component.

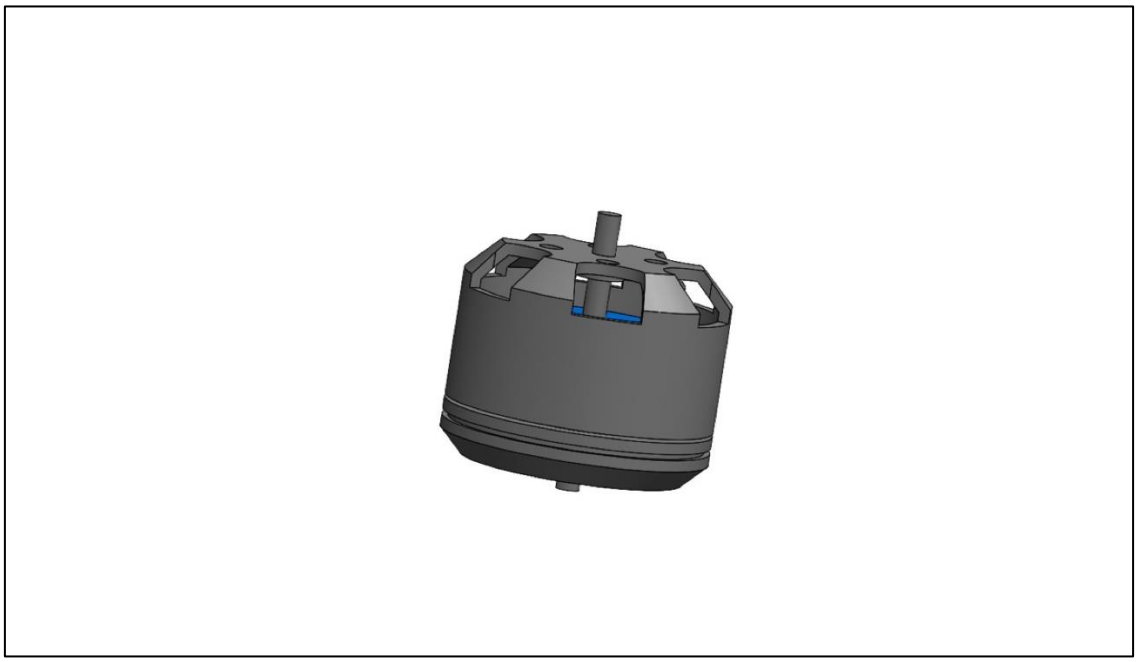


Figure 20: SOLIDWORKS model of the motor component.

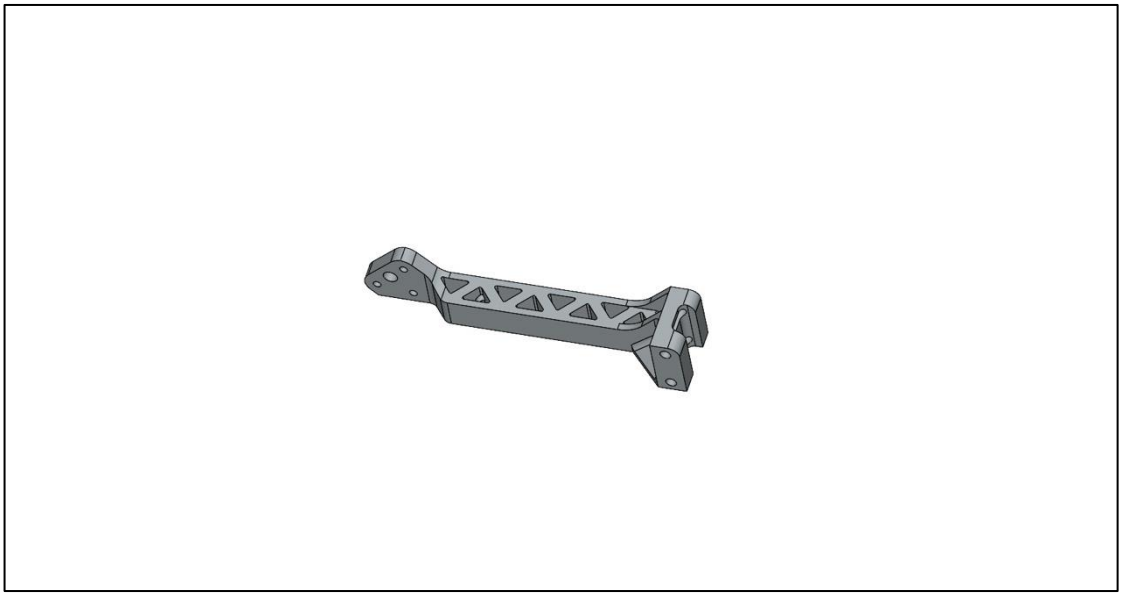


Figure 21: SOLIDWORKS model of the spider arm component.

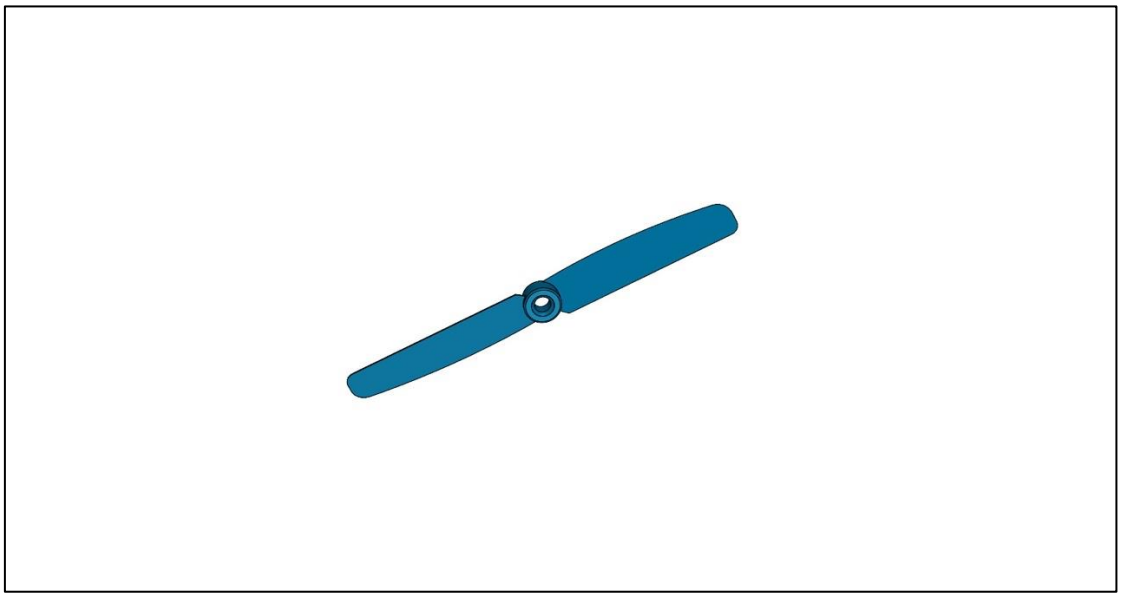


Figure 22: SOLIDWORKS model of the fan component.

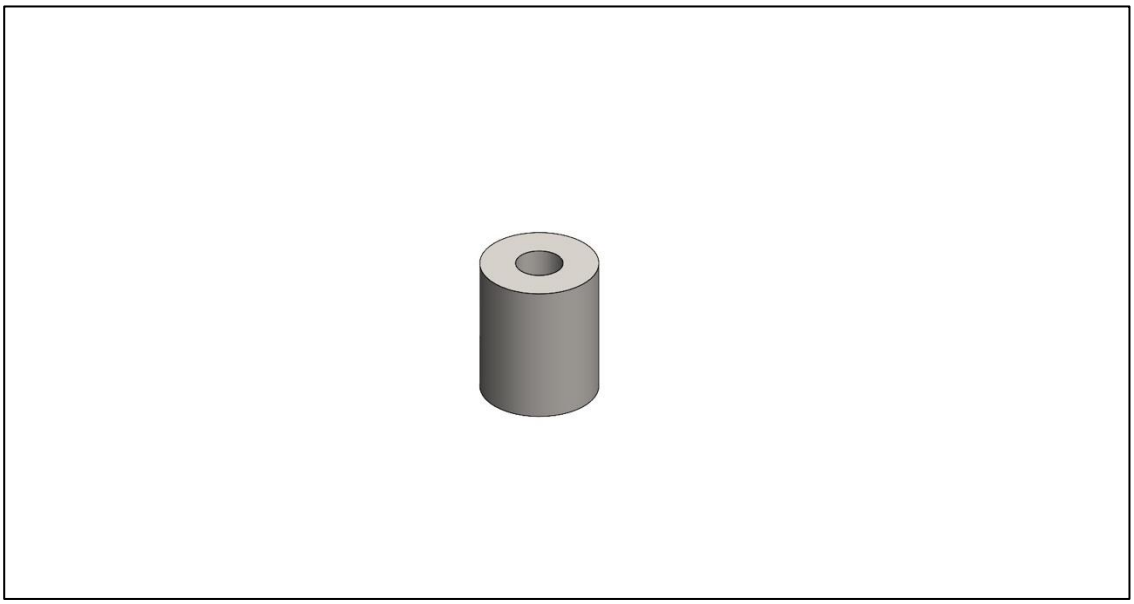


Figure 23: SOLIDWORKS model of the spacer component

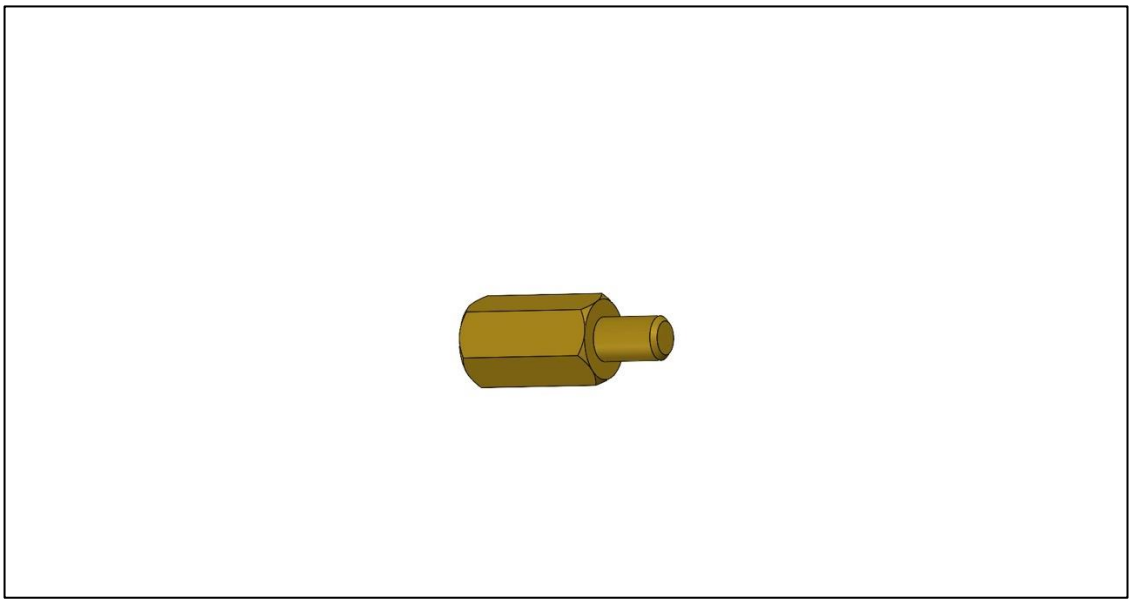


Figure 24: SOLIDWORKS model of the pillar component.

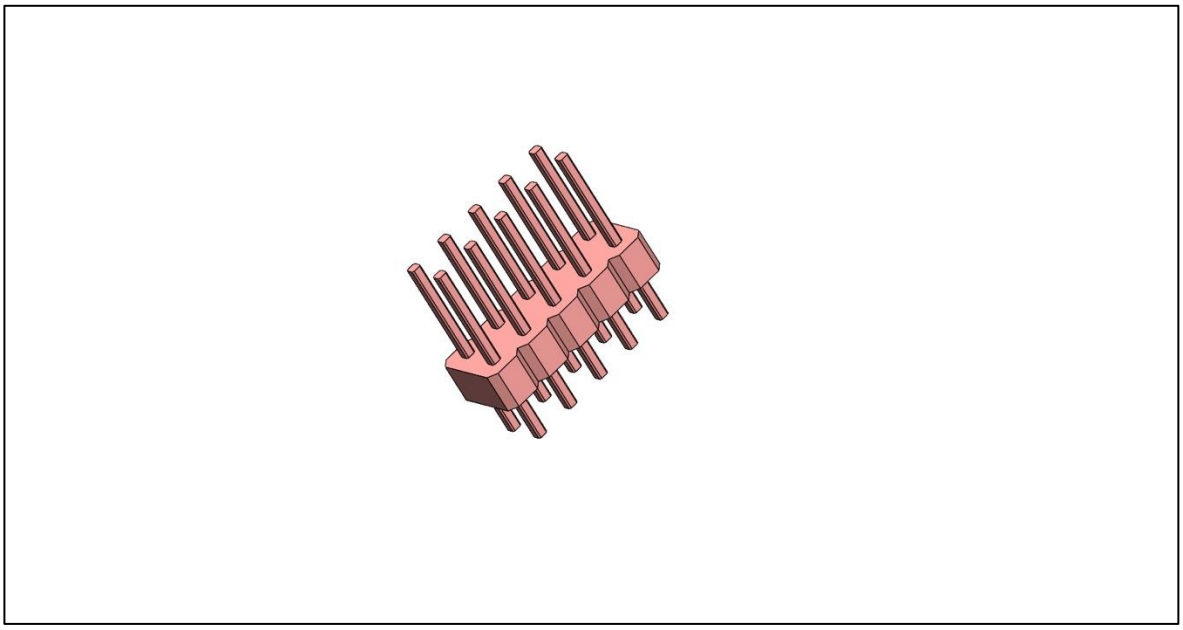


Figure 25: SOLIDWORKS model of the electrical unit 1 component.

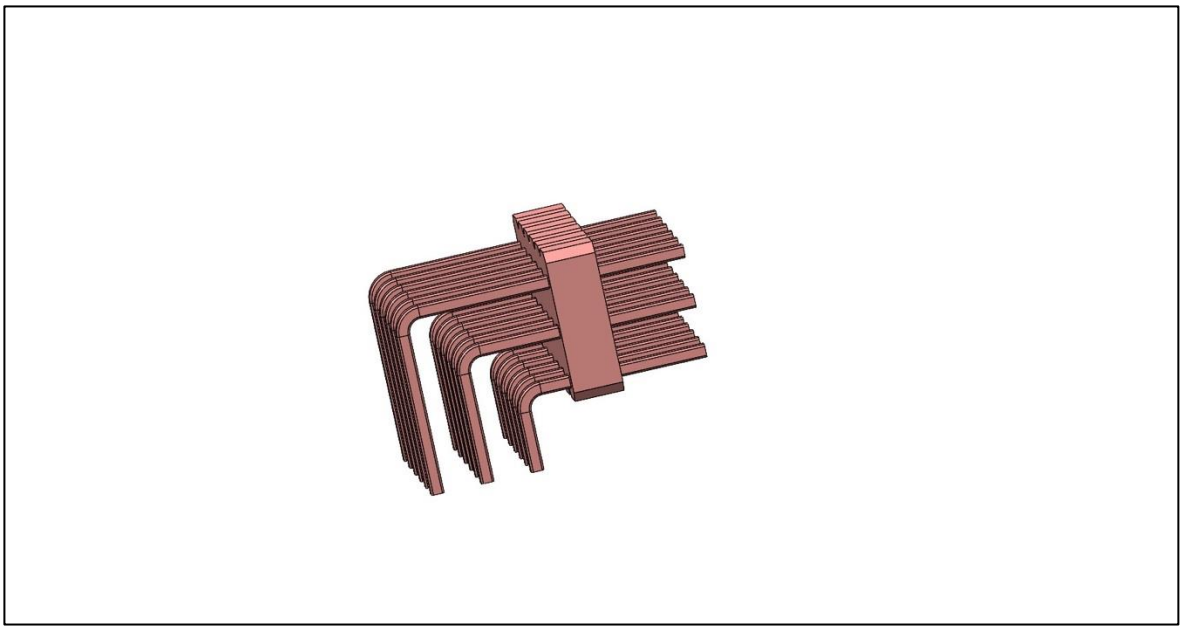


Figure 26: SOLIDWORKS model of the electrical unit 2 component.

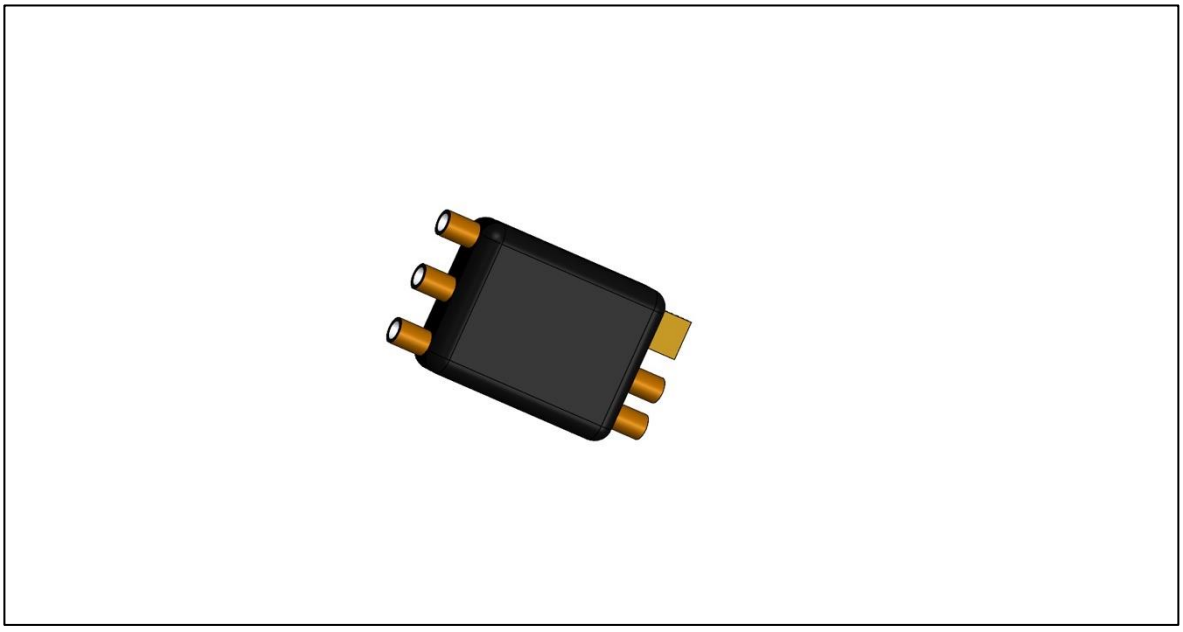


Figure 27: SOLIDWORKS model of the electrical connector component.

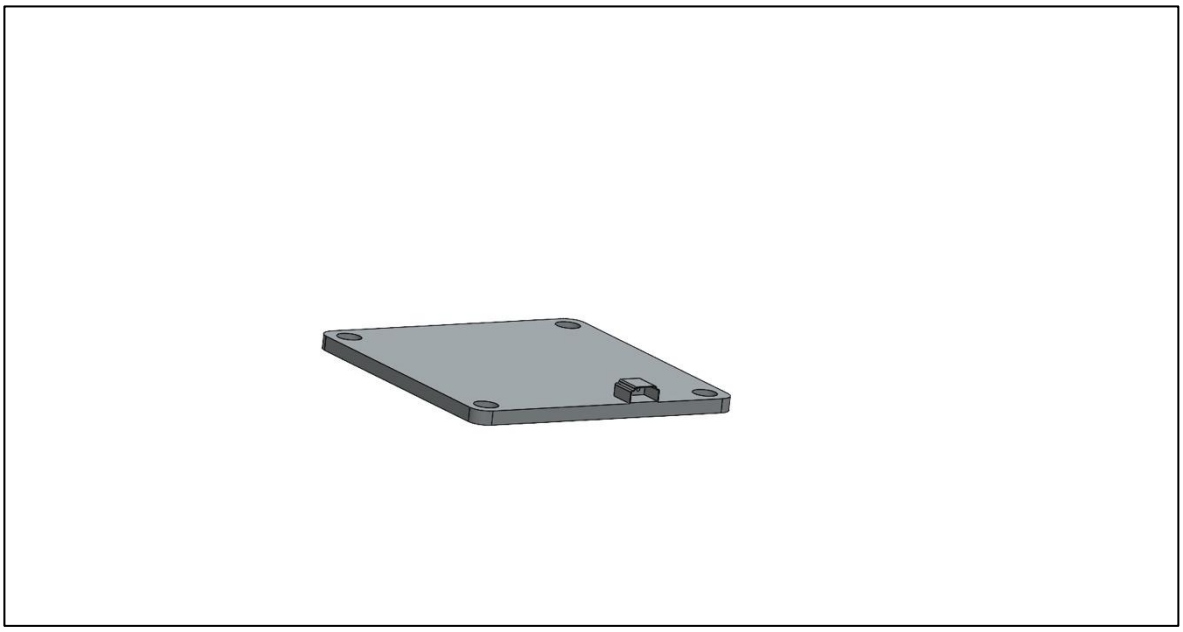


Figure 28: SOLIDWORKS model of the distribution board component.

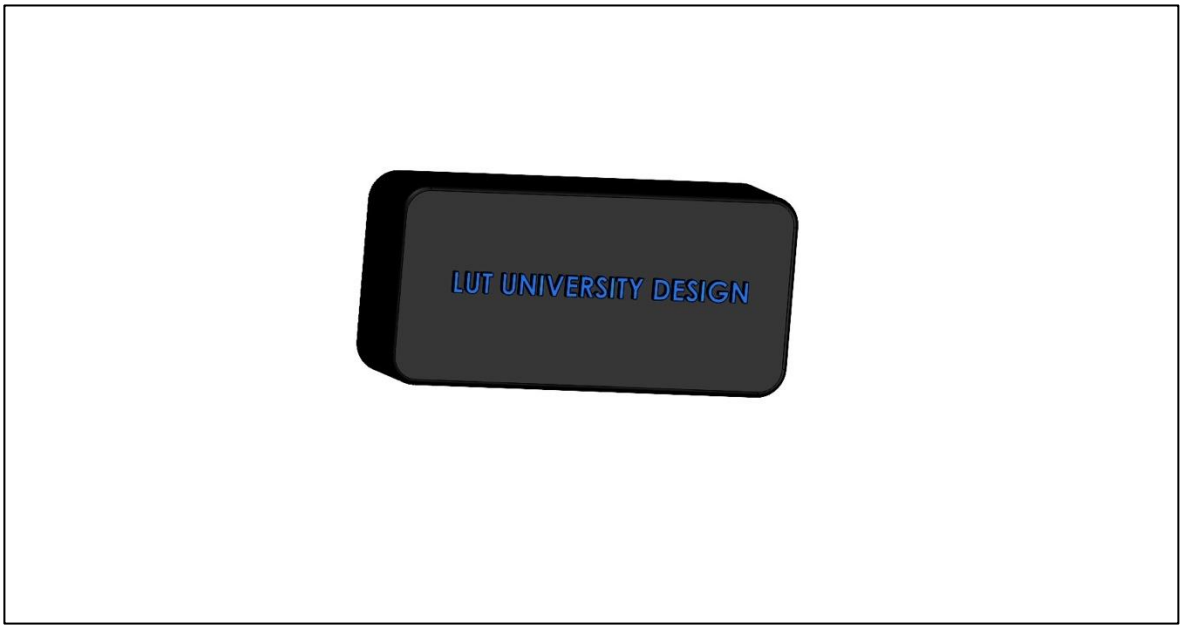
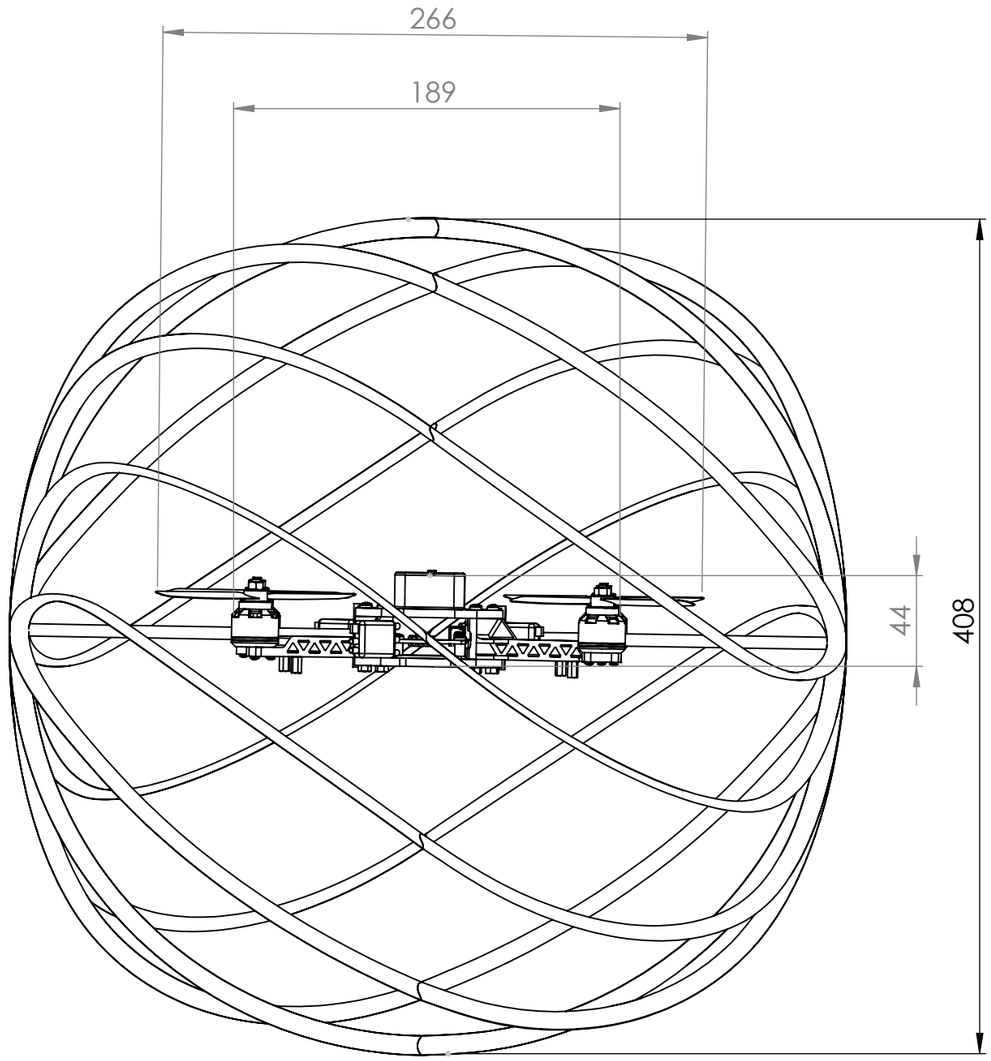
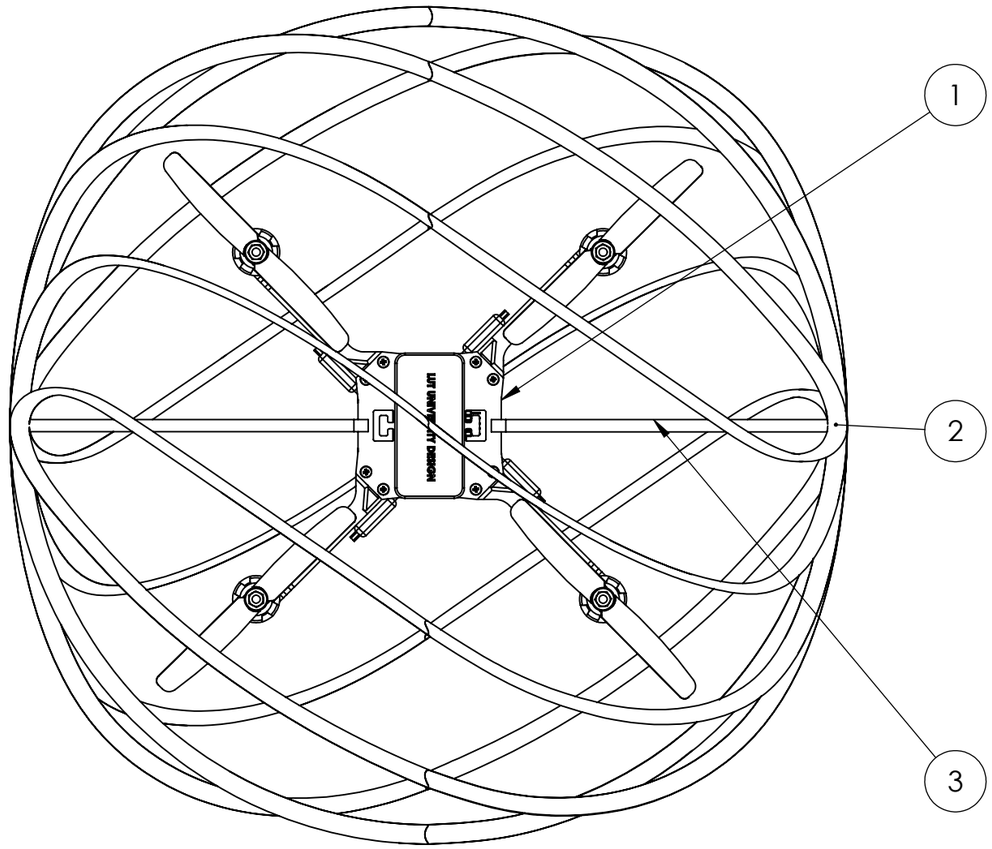


Figure 29: SOLIDWORKS model of the battery component.

Appendix 2. CAD Drawings of the Cage Drone Robot Assembly and Components

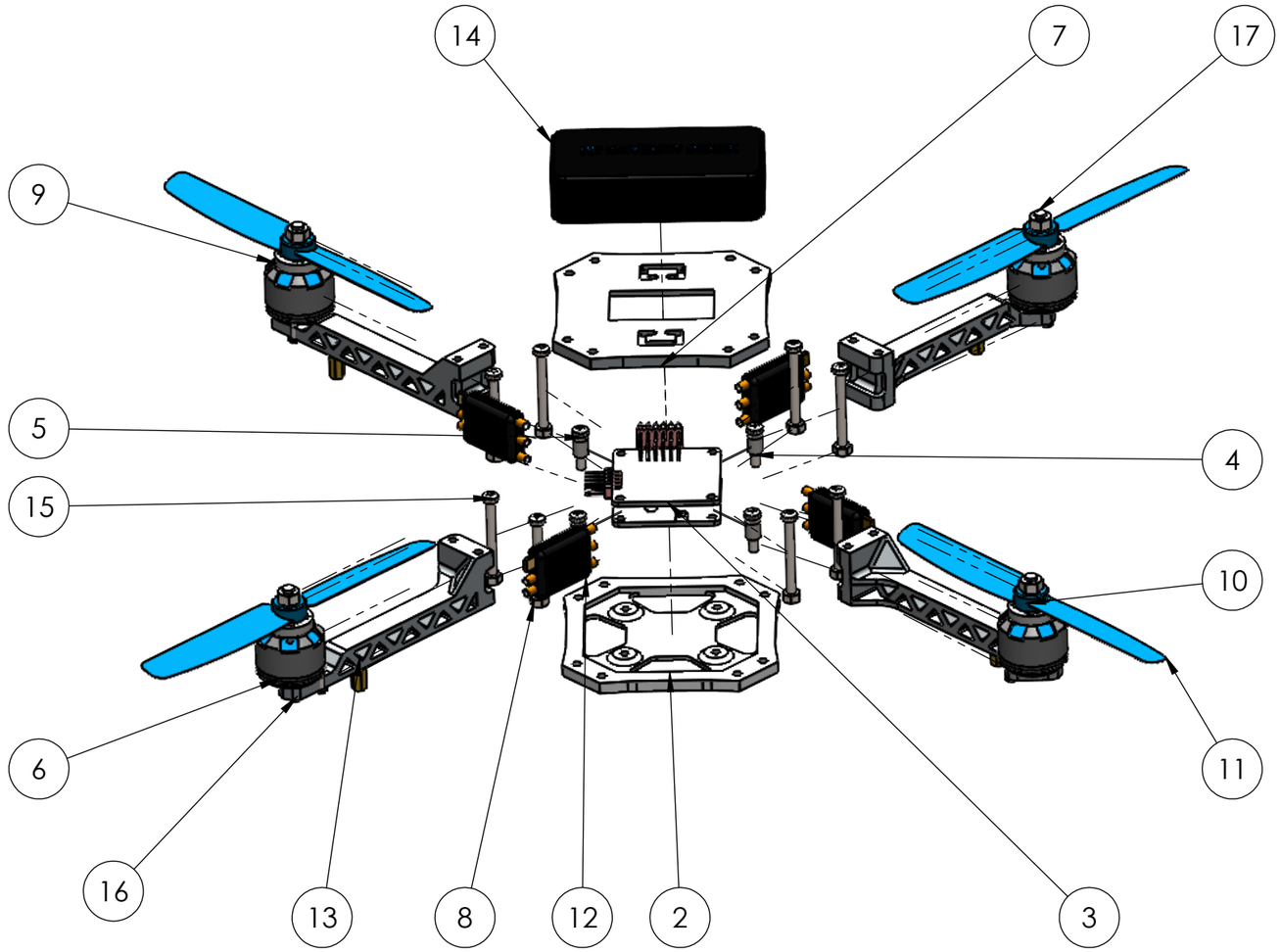




ITEM NO.	PART DESCRIPTION	COMPOSITION OR MATERIAL	QTY.
1	Drone Assembly	Exterior drone components (CDR-001), Interior drone components (CDR-002)	1
2	Drone Cage	Aluminium (CDR-003)	1
3	Connecting rod	Aluminium (CDR-004)	2

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Cage drone robot assembly	
DRAWN	Evgeniia Efimenko		02.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO.	A3
				WEIGHT:		SCALE:1:10	SHEET 1 OF 1

ITEM NO.	PART DESCRIPTION	QTY.
1	Distribution Board	1
2	Spider Base	1
3	Electrical enclosure	1
4	Spacer	4
5	B18.6.7M - M3 x 0.5 x 13 Type I Cross Recessed PHMS -- 13N	4
6	Spider Arm	4
7	Spider Top	1
8	B18.2.4.2M - Hex nut, Style 2, M3 x 0.5 --D-N	8
9	Motor	4
10	Spinner	4
11	Fan	4
12	Electrical Connector	4
13	Pillar	4
14	Battery	1
15	B18.6.7M - M3 x 0.5 x 30 Type I Cross Recessed PHMS -- 30N	8
16	B18.6.7M - M2 x 0.4 x 6 Type I Cross Recessed PHMS -- 6N	12
17	B18.2.4.2M - Hex nut, Style 2, M4 x 0.7 --D-N	4



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

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Evgeniia Efimenko		10.04.24
CHK'D	Evgeniia Efimenko		07.05.24
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

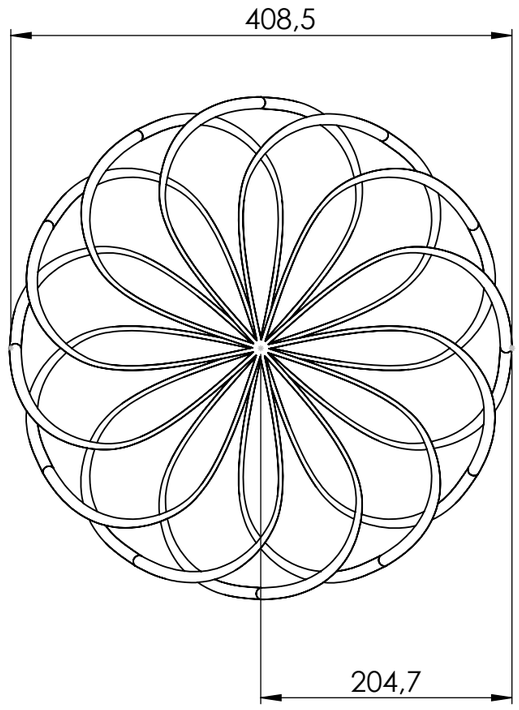
Drone Assembly

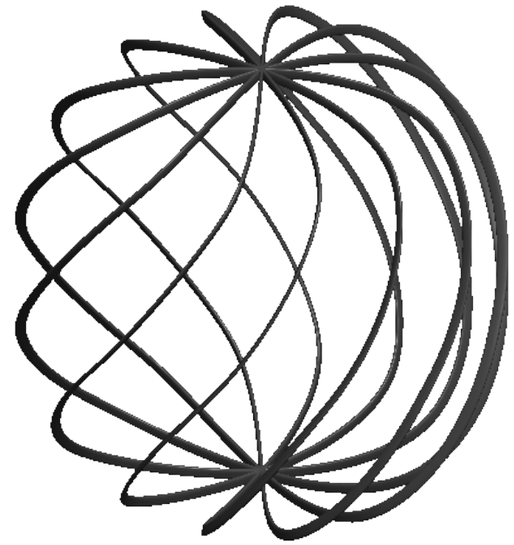
DWG NO. CDR-001, CDR-002

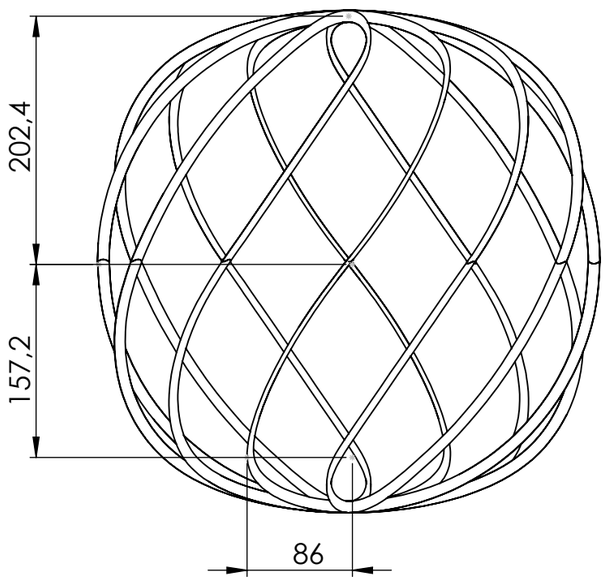
A3

SCALE:1:5

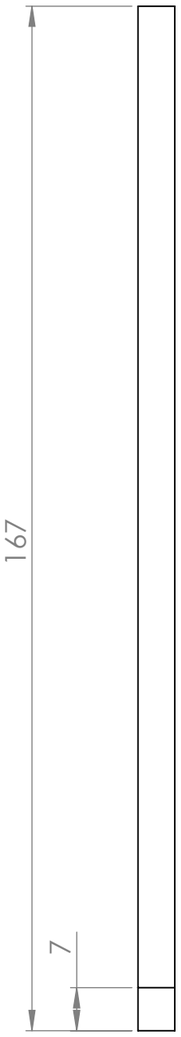
SHEET 1 OF 1

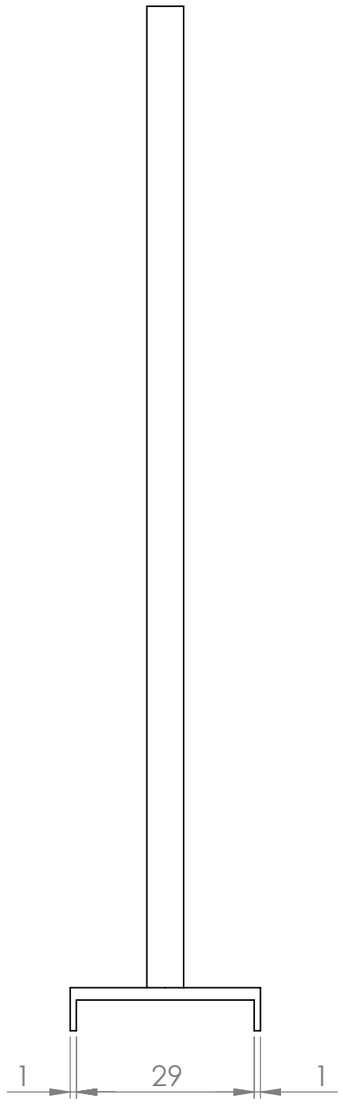


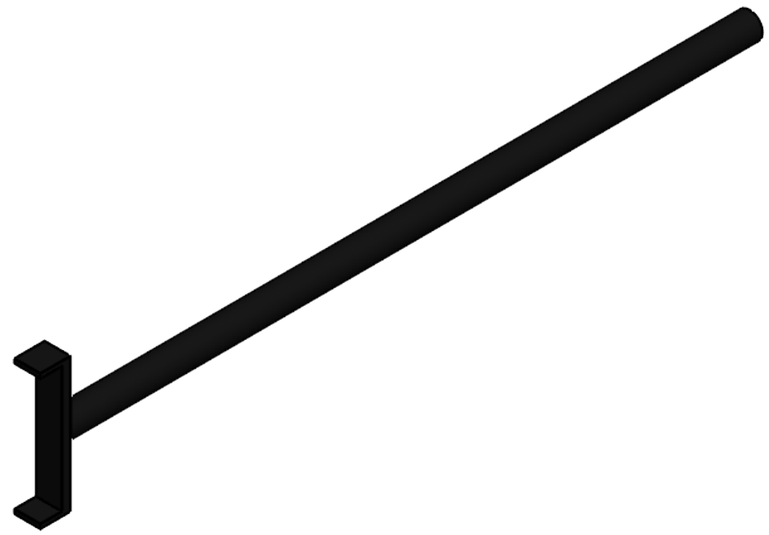


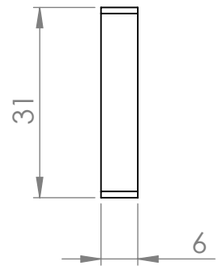


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Drone Cage	
DRAWN	Evgeniia Efimenko		04.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Nylon 6		DWG NO. CDR-003	A3
				WEIGHT:		SCALE:1:10	SHEET 1 OF 1



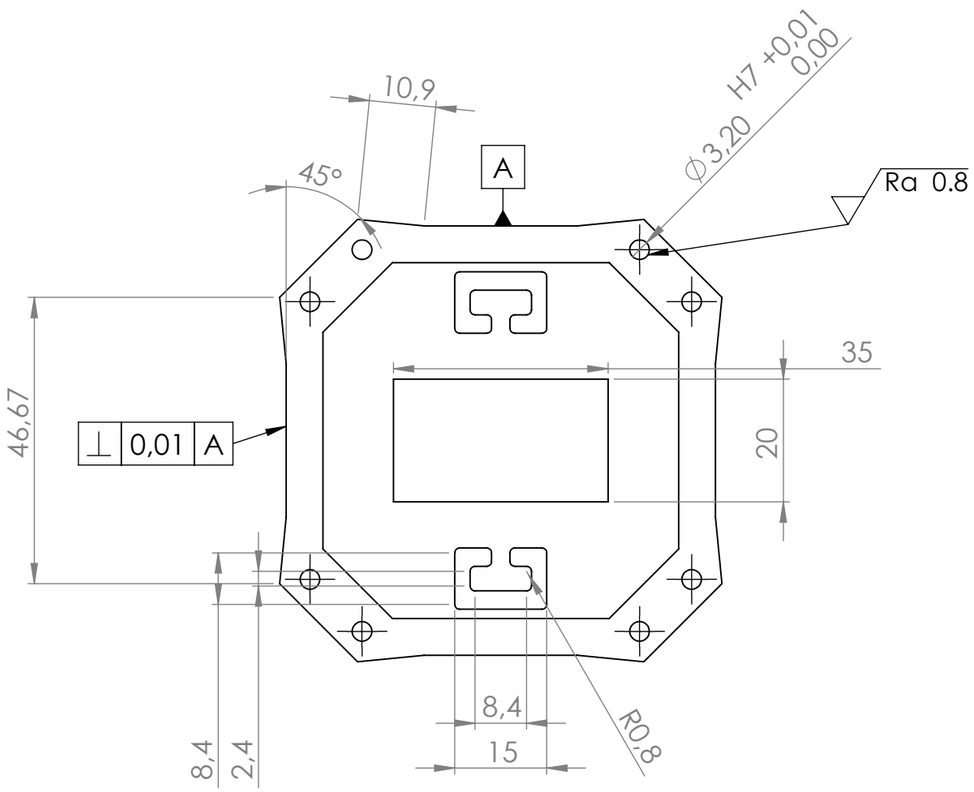


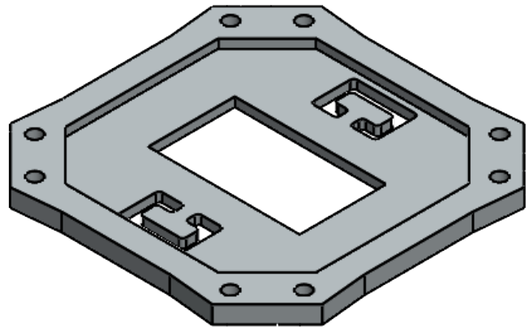


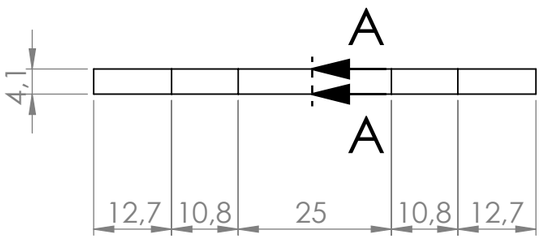


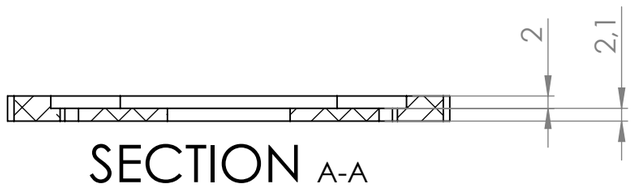
Ra 0.8

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Evgeniia Efimenko		04.04.24			Connecting rod	
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Carbon steel		DWG NO. CDR-004	A3
				WEIGHT:		SCALE:1:2	SHEET 1 OF 1





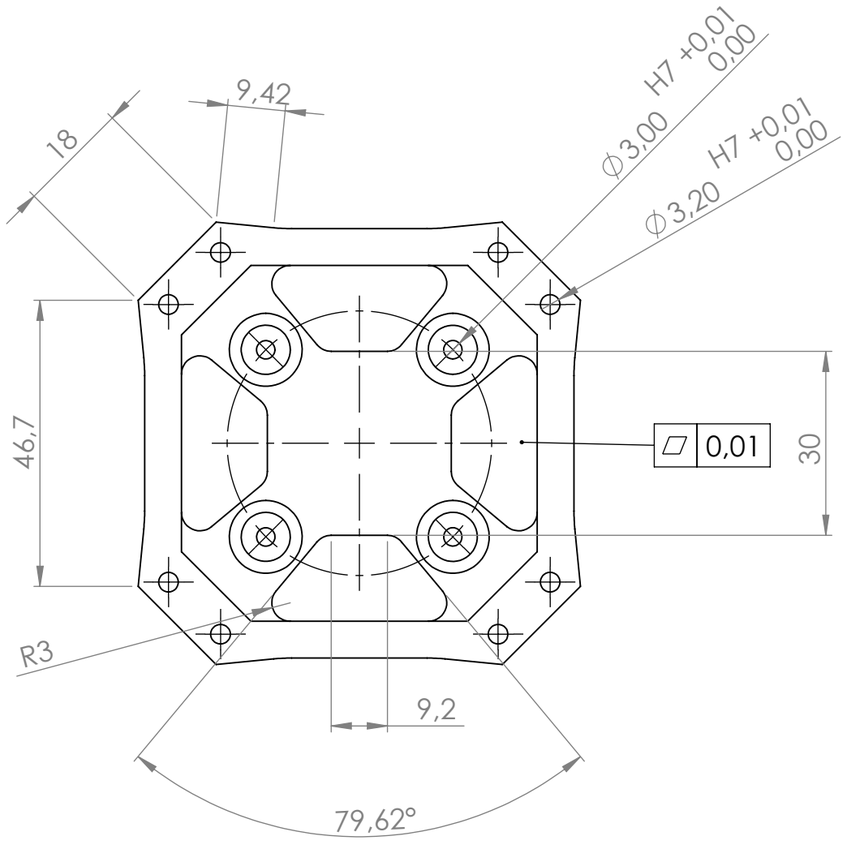


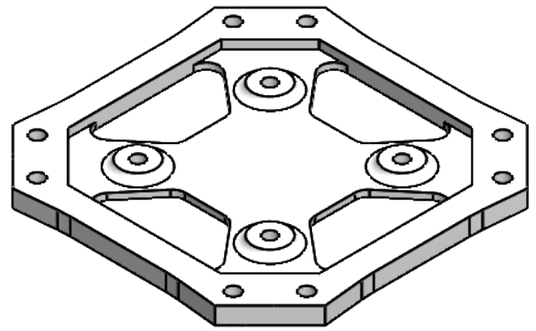


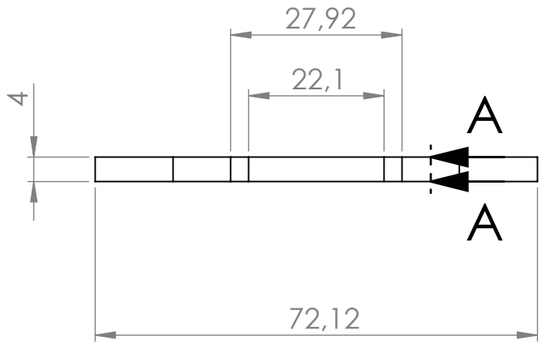
SECTION A-A

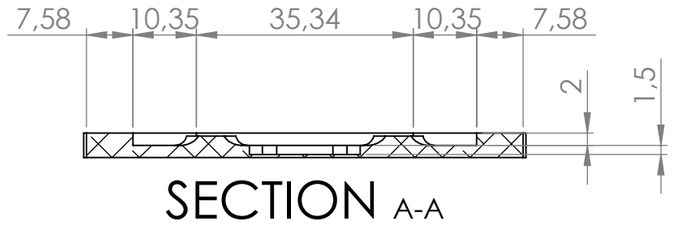
Ra 1.6 (Ra 0.8)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Evgeniia Efimenko		04.04.24			Spider Top	
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO.	A3
				Aluminium alloy 2024		CDR-001-002	
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1





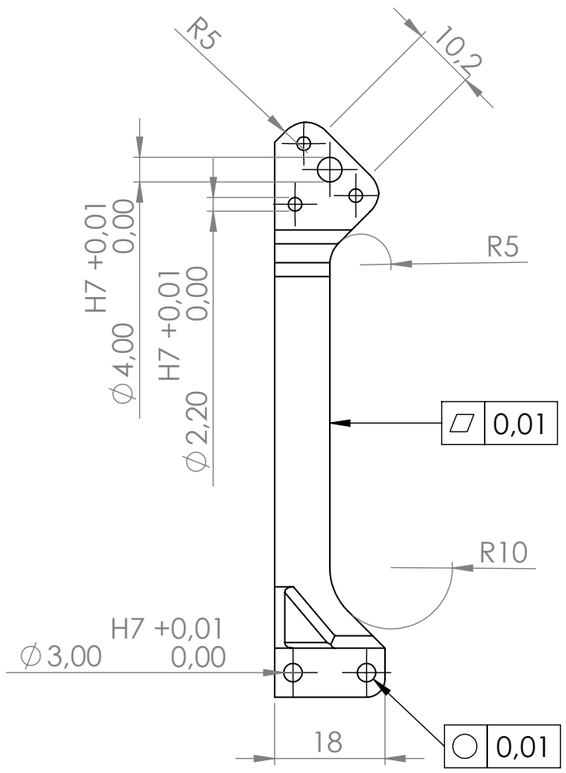


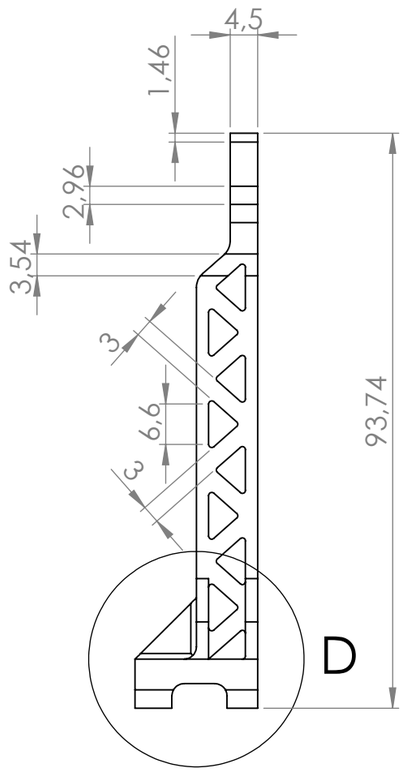


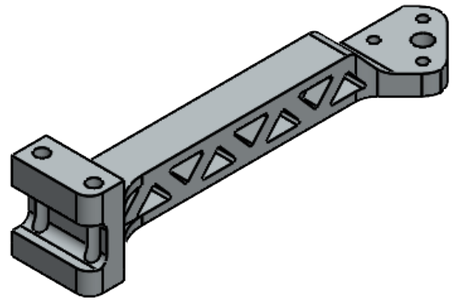
SECTION A-A

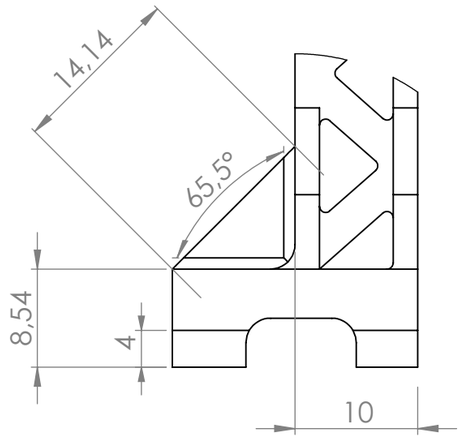
Ra 1.6

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Evgeniia Efimenko		04.04.24			Spider Base	
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO.	A3
				Aluminium alloy 2024		CDR-001-001	
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1



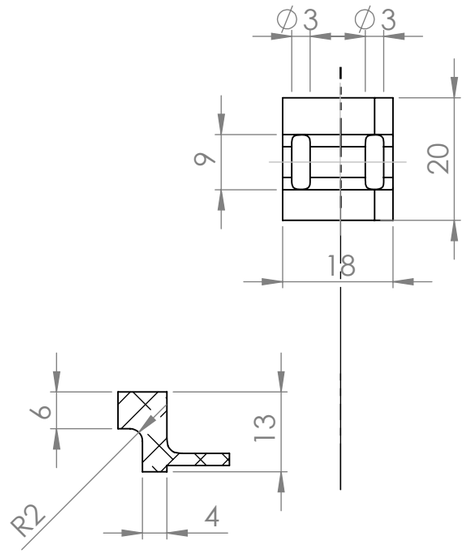






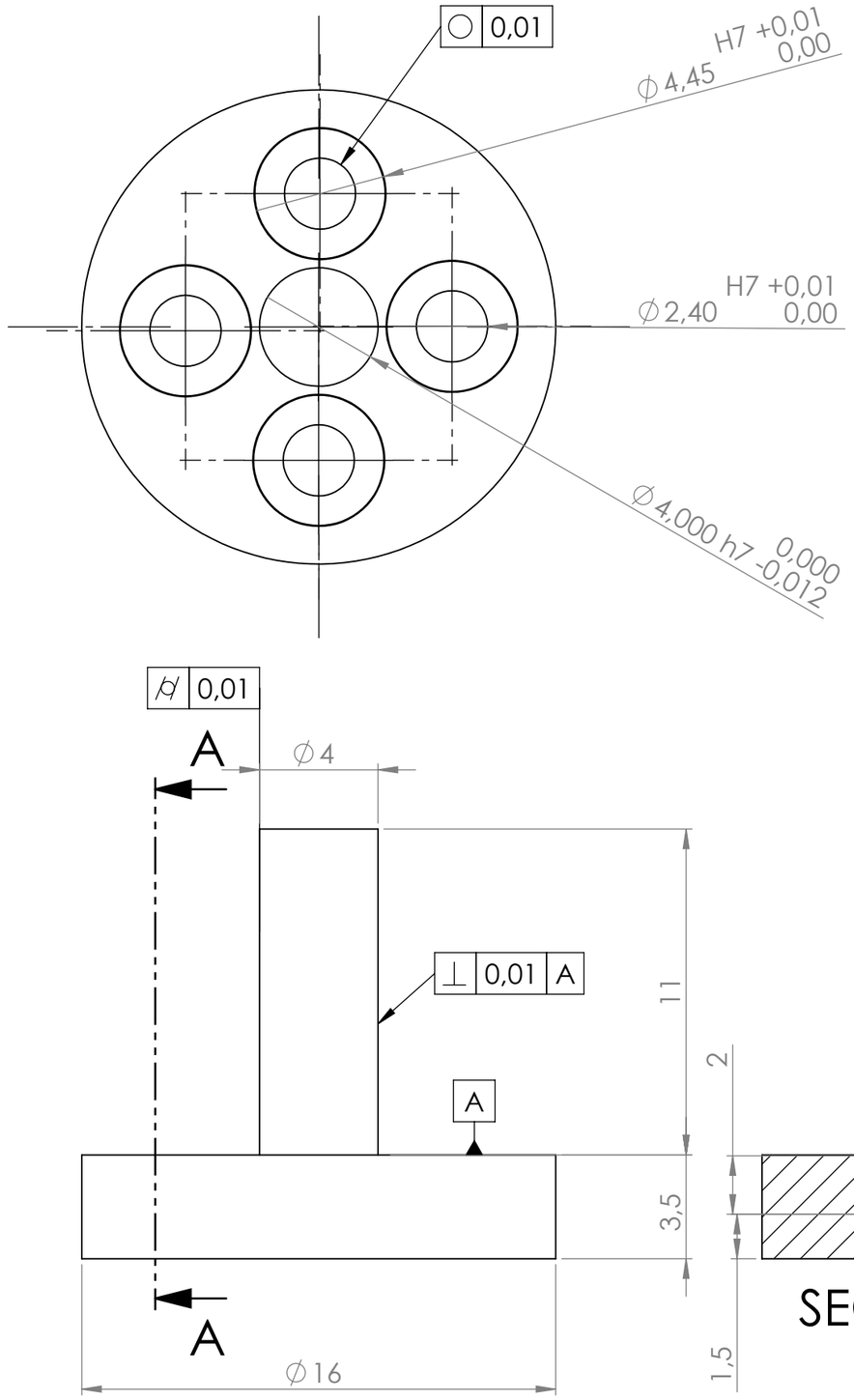
DETAIL D

SCALE 2 : 1

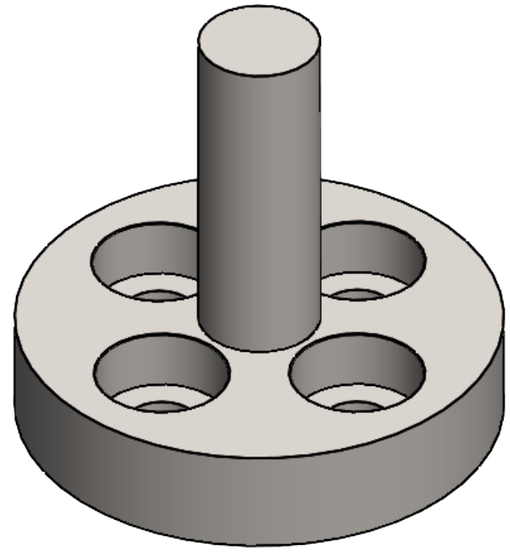


Ra 1.6

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Spider Arm	
DRAWN	Evgeniia Efimenko		08.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Aluminium alloy 2024		DWG NO. CDR-001-003	A3
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1

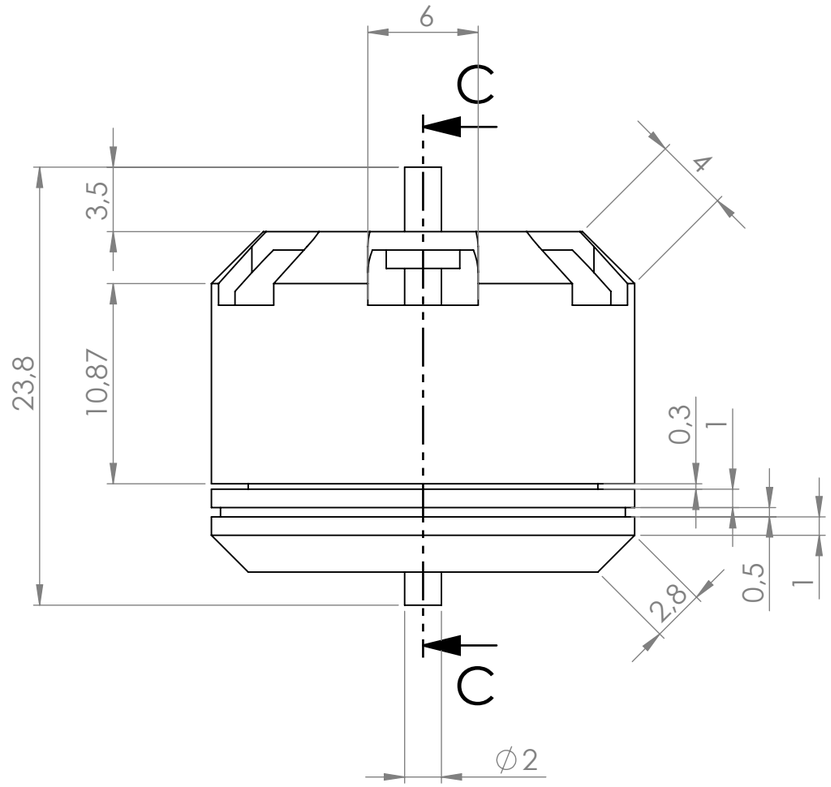


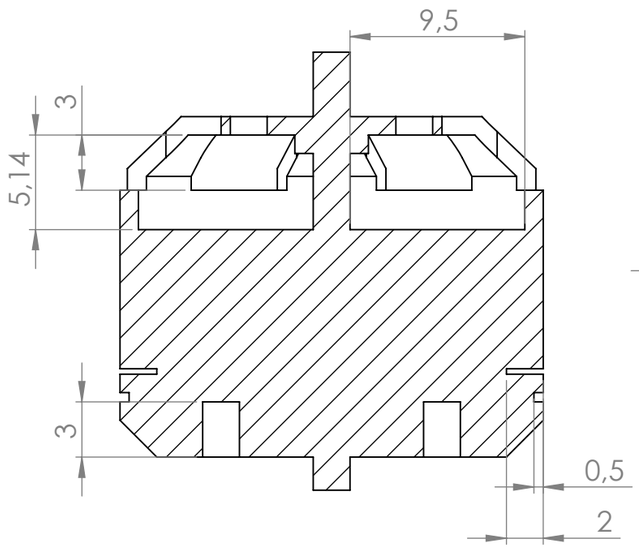
SECTION A-A



Ra 0.8

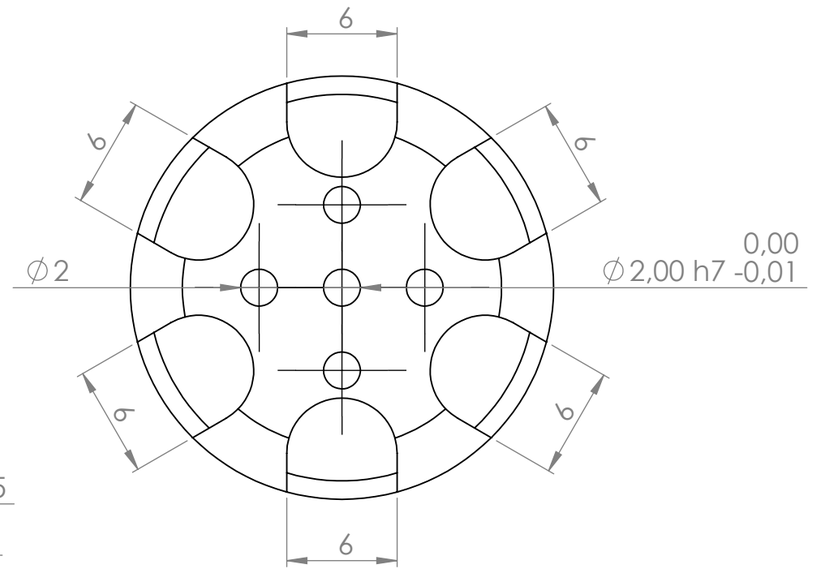
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Spinner	
DRAWN	Evgeniia Efimenko		04.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Carbon steel		DWG NO. CDR-002-001	A3
				WEIGHT:		SCALE:5:1	SHEET 1 OF 1

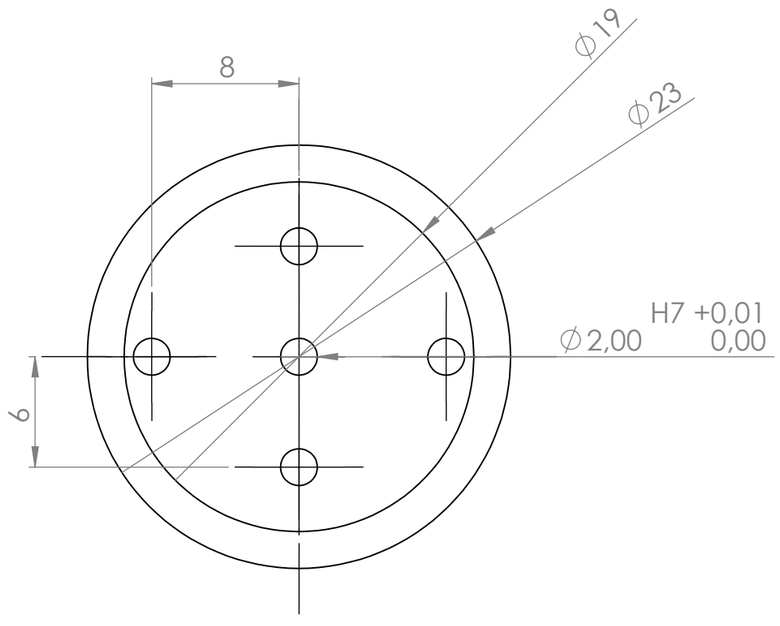


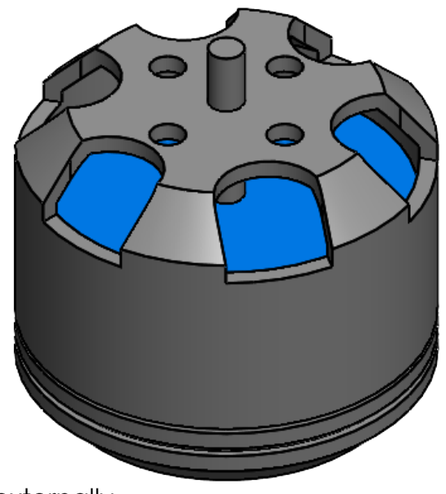


SECTION C-C

SCALE 3 : 1

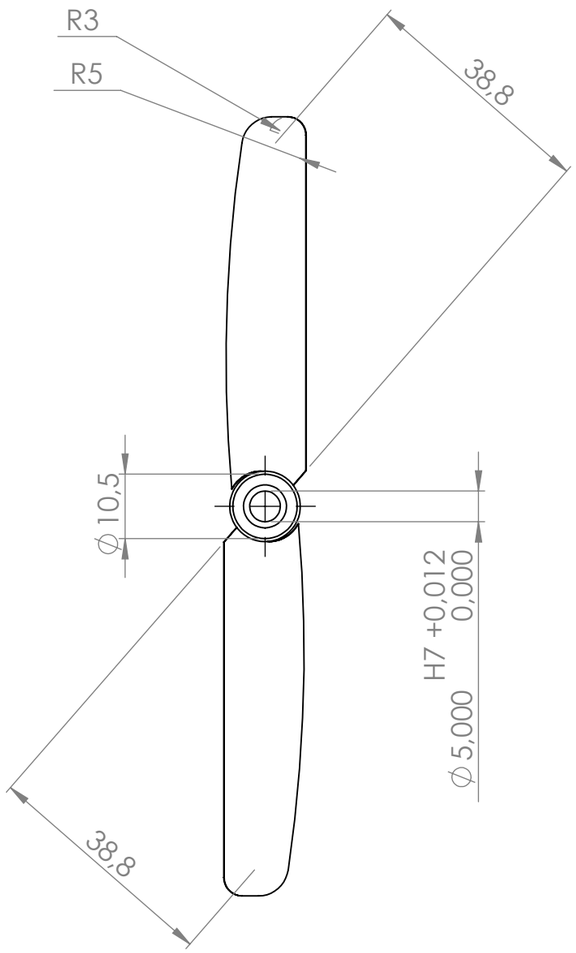


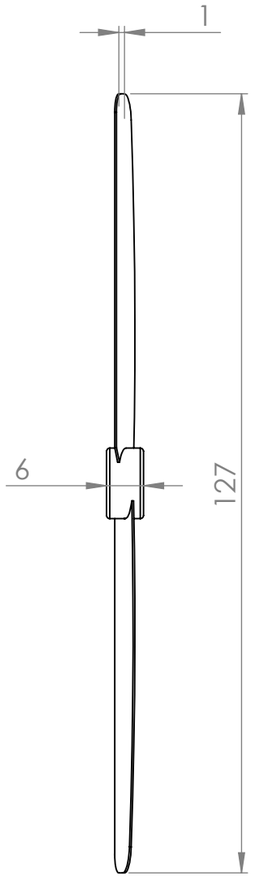


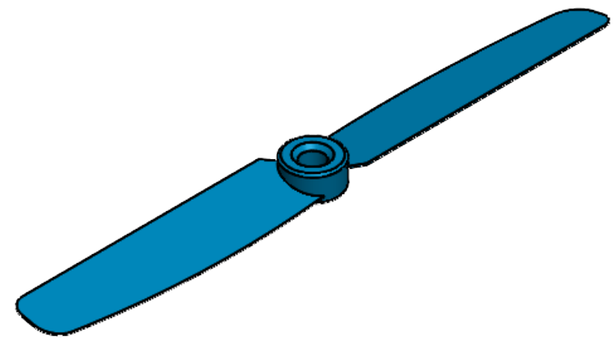


Note: part is to be purchased externally.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Evgeniia Efimenko		10.04.24			Motor	
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO. CDR-002-006	A3
				WEIGHT:		SCALE:2:1	SHEET 1 OF 1

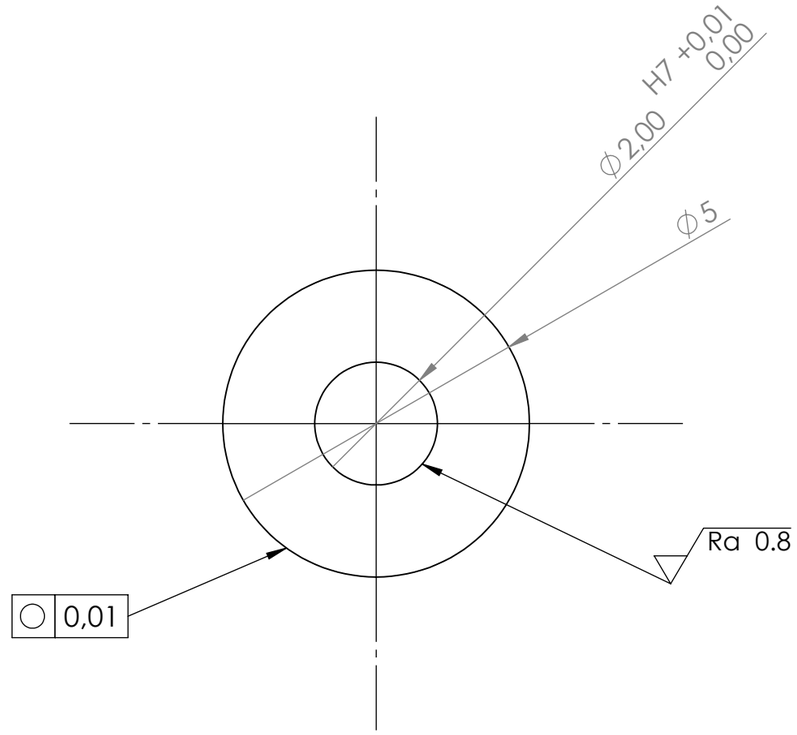


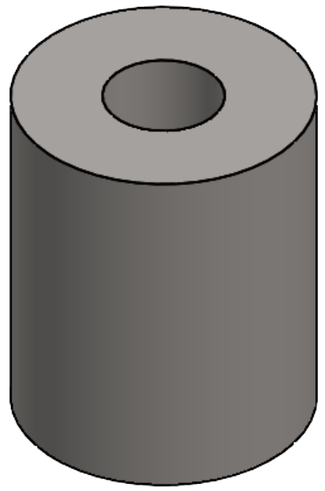


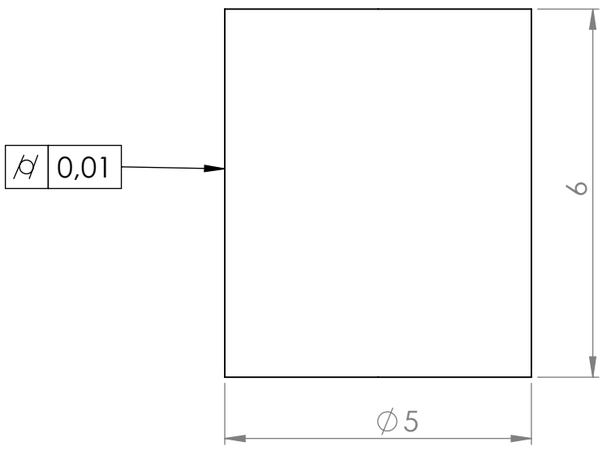


Ra 0.6

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Fan	
DRAWN	Evgeniia Efimenko		08.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Aluminium alloy 2024		DWG NO. CDR-001-004	A3
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1

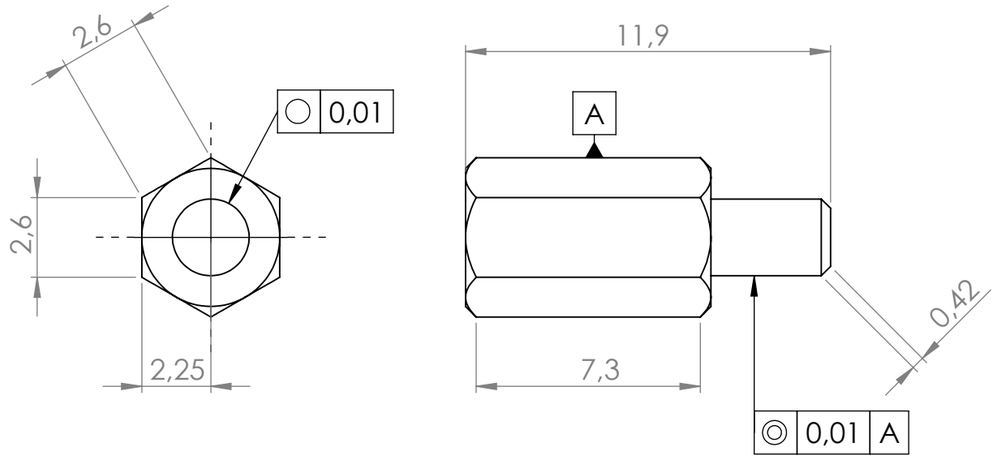


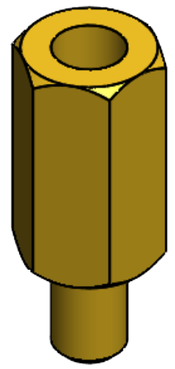


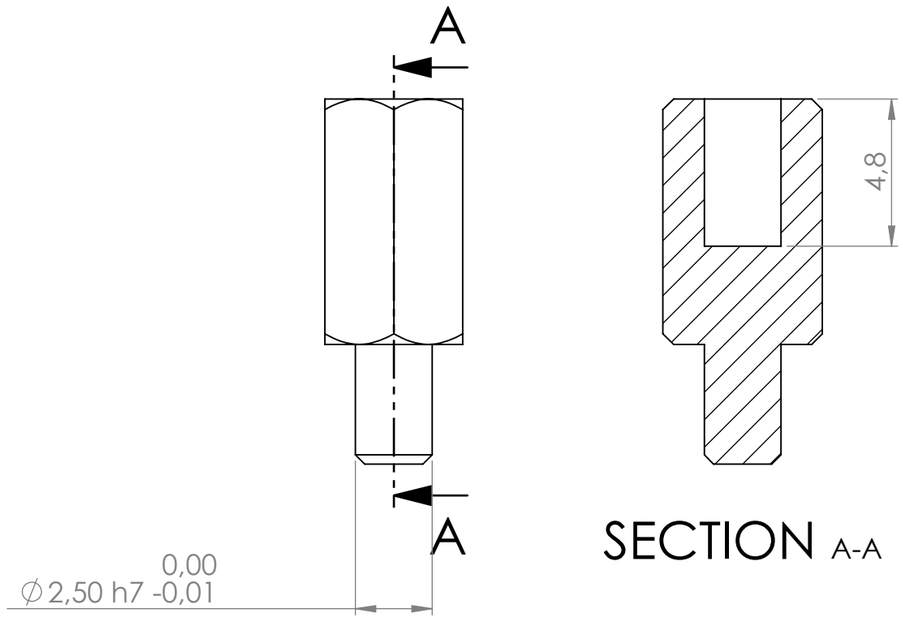


Ra 1.6 (Ra 0.8)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Spacer	
DRAWN	Evgeniia Efimenko		04.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Aluminium alloy 2024		DWG NO. CDR-002-002	A3
				WEIGHT:		SCALE:10:1	SHEET 1 OF 1



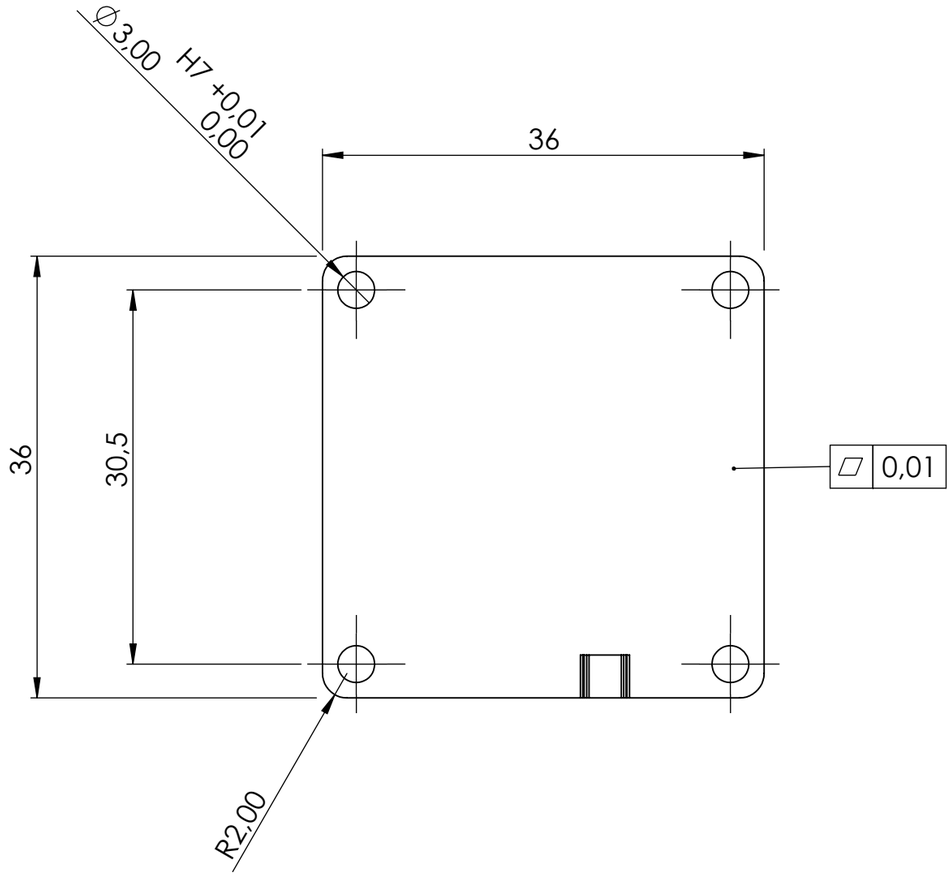


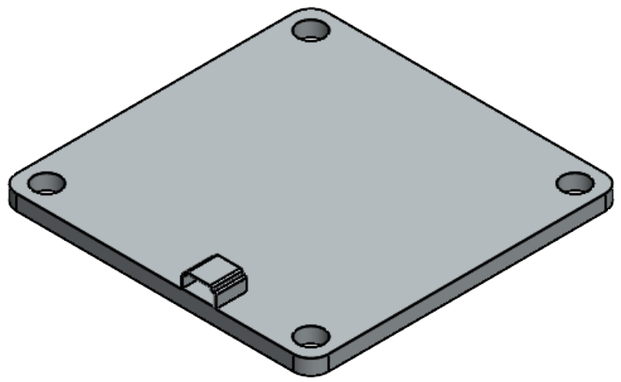


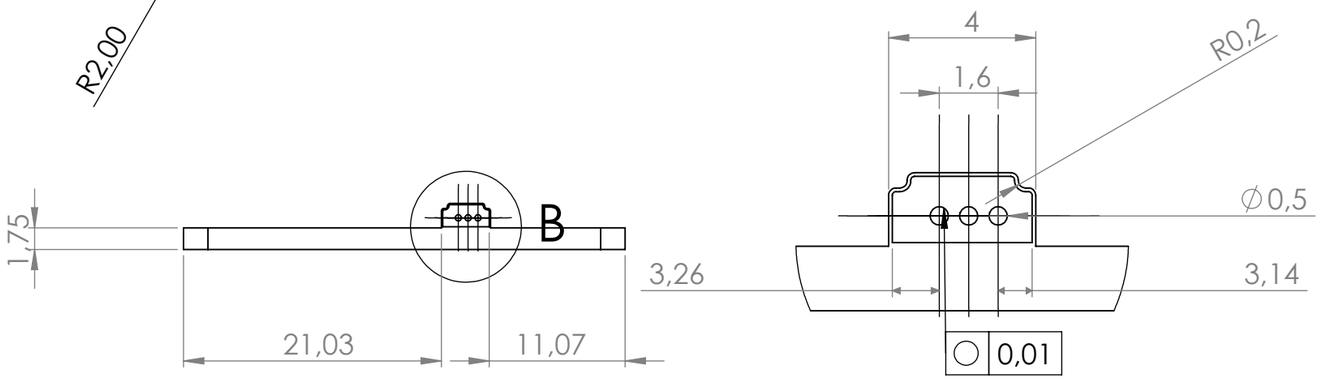
SECTION A-A

Ra 1.6

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Evgeniia Efimenko		08.04.24			Pillar	
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO.	A3
				Carbon steel		CDR-002-004	
				WEIGHT:		SCALE:5:1	SHEET 1 OF 1





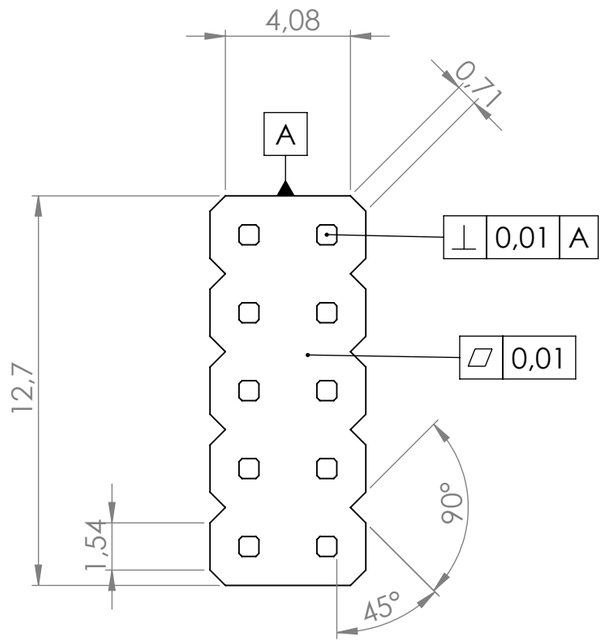


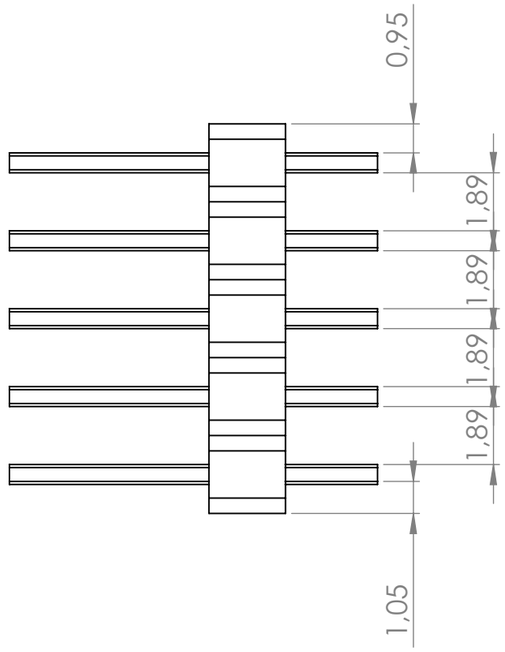
DETAIL B

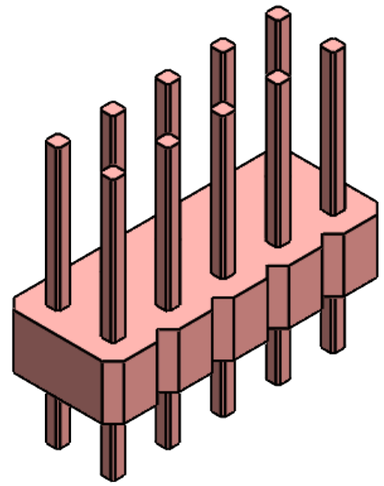
SCALE 6 : 1

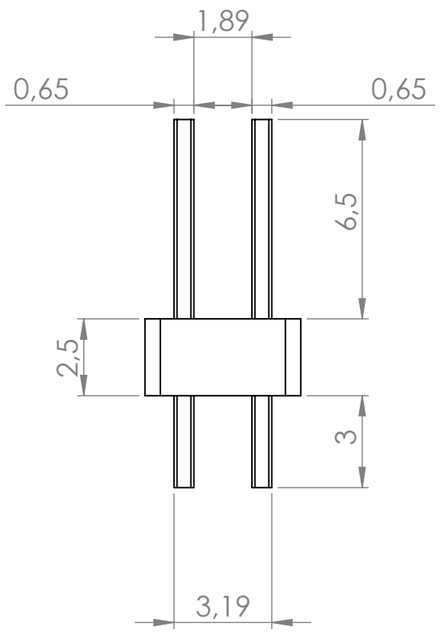
Ra 0.6

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Distribution Board	
DRAWN	Evgeniia Efimenko		08.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Copper (L)		DWG NO. CDR-002-005	A3
				WEIGHT:		SCALE:2:1	SHEET 1 OF 1



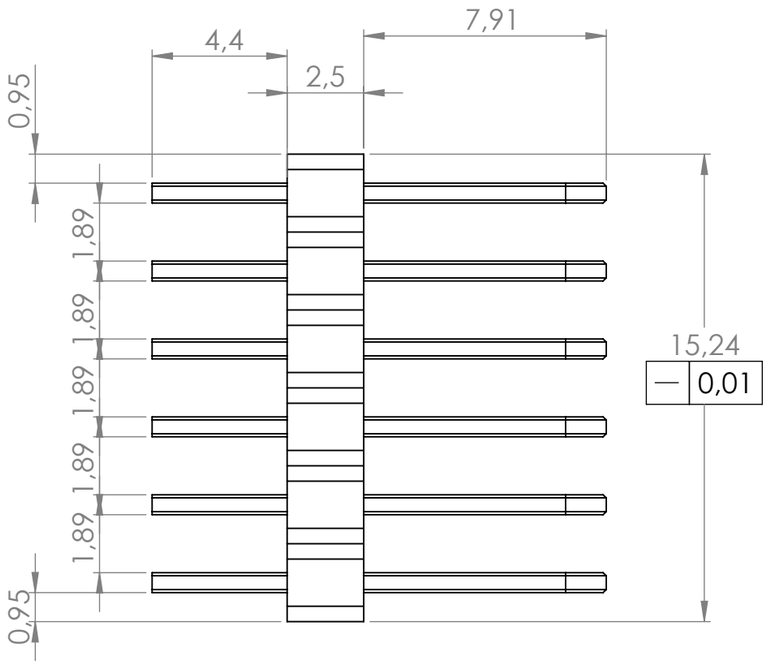


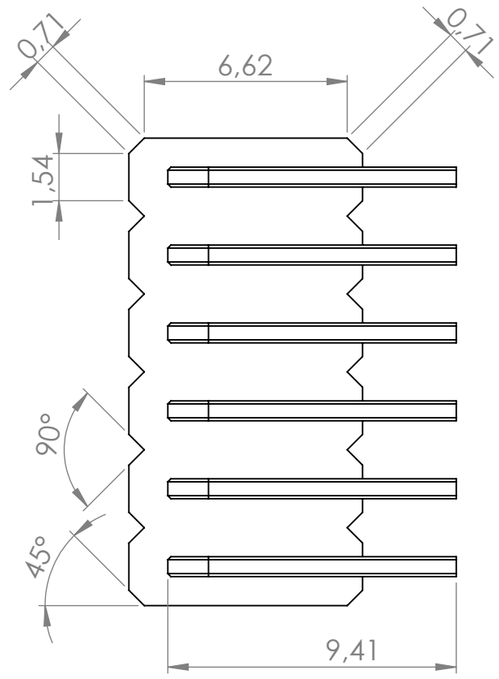


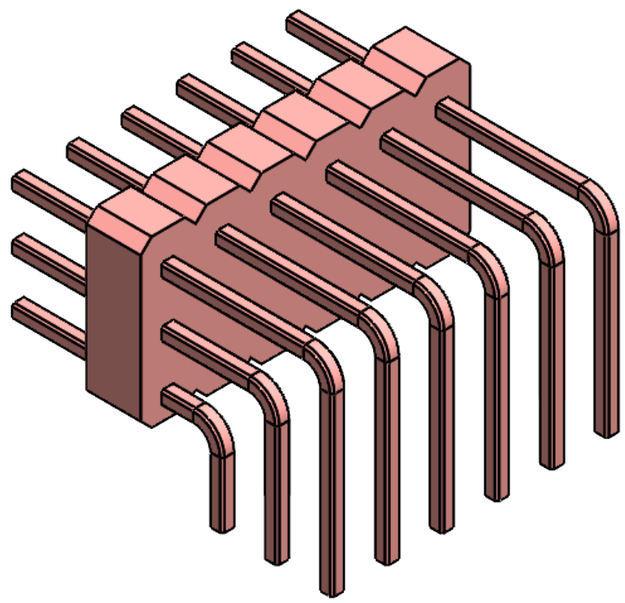


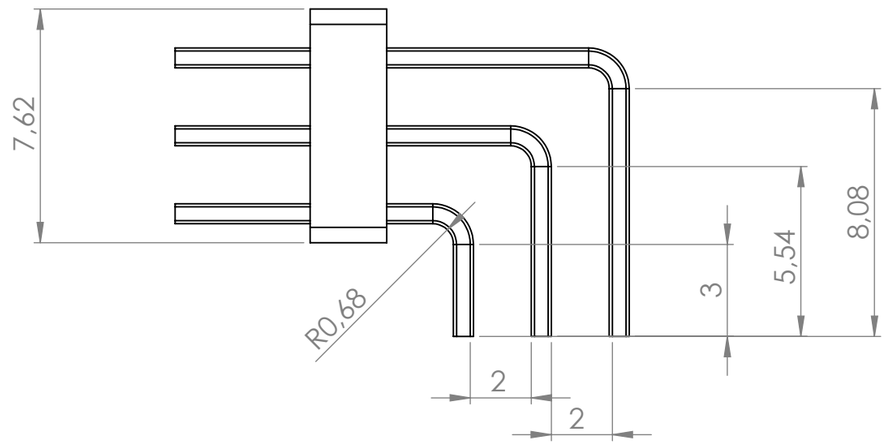
Ra 0.8

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: Electrical Unit 1	
DRAWN	Evgeniia Efimenko		08.04.24				
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Copper (L)		DWG NO. CDR-002-008	A3
				WEIGHT:		SCALE:5:1	SHEET 1 OF 1



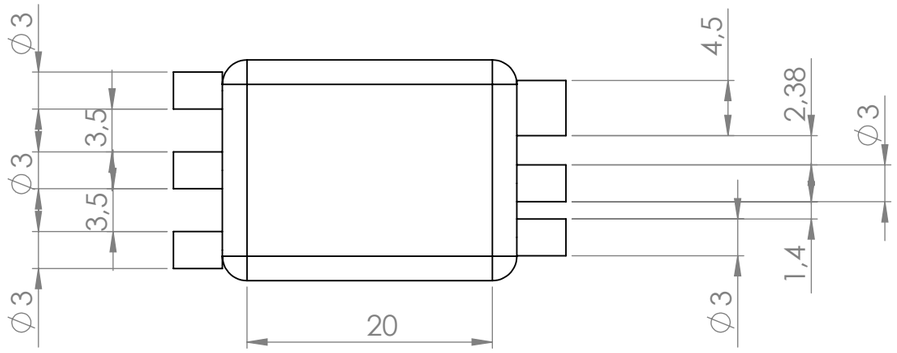


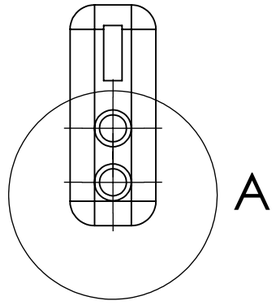


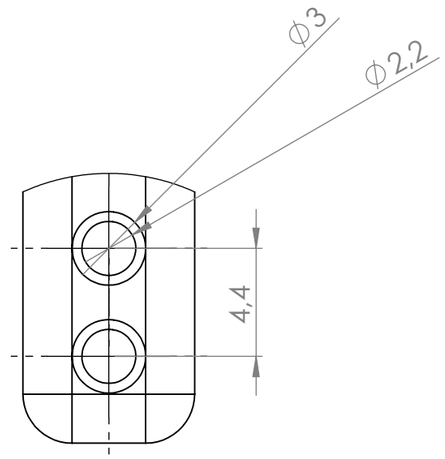


Ra 0.8

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO 2768 medium LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Evgeniia Efimenko		10.04.24			Electrical Unit 2	
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL: Copper (L)		DWG NO. CDR-002-009	A3
				WEIGHT:		SCALE:5:1	SHEET 1 OF 1

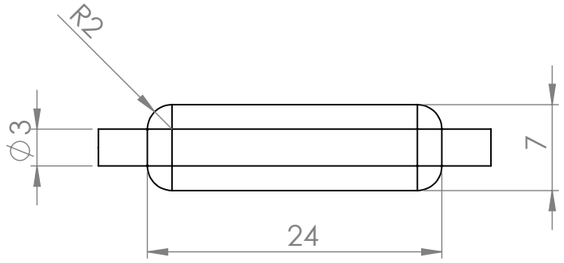


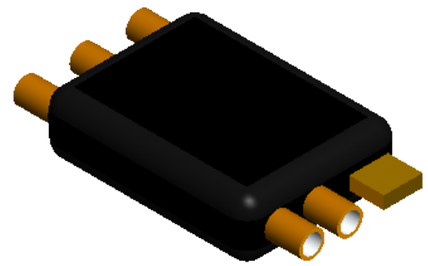




DETAIL A

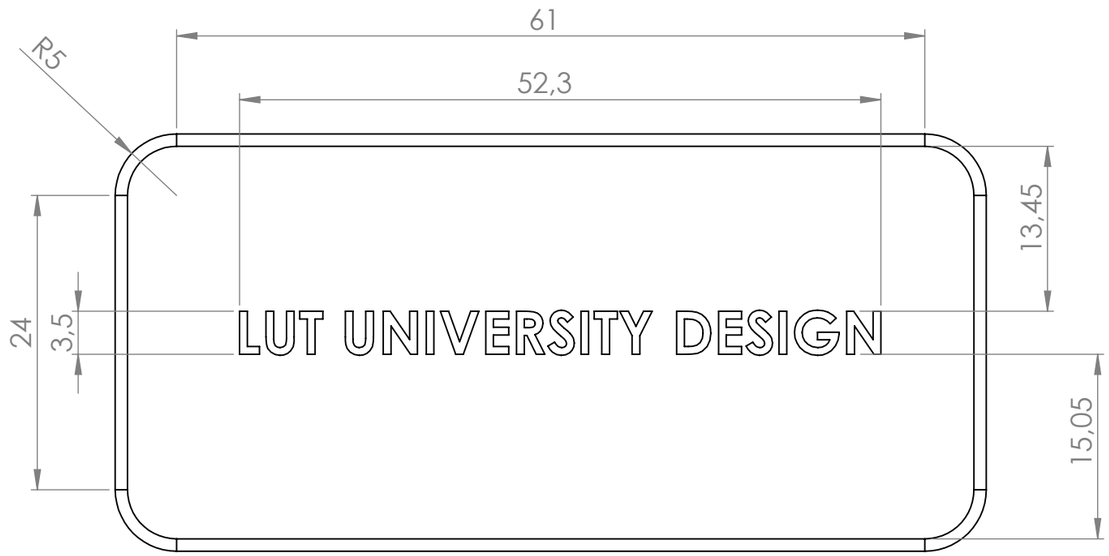
SCALE 4 : 1

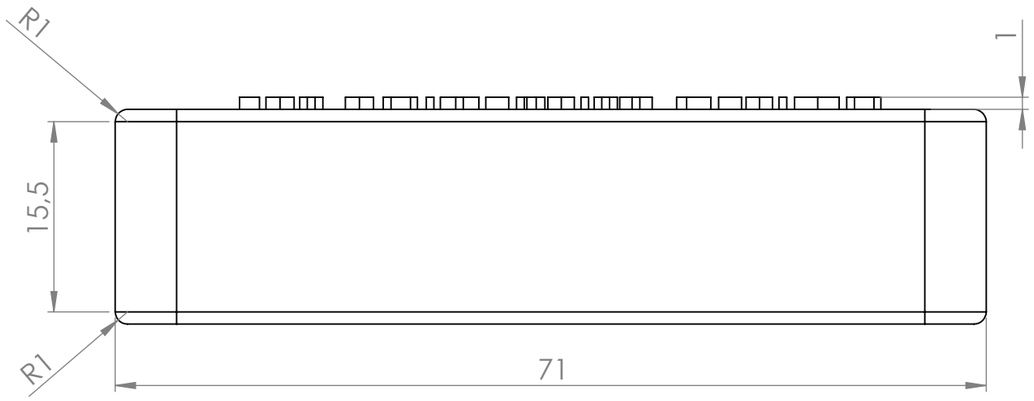




Note: part to be purchased externally.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	Evgeniia Efimenko		04.04.24			Electrical Connector	
CHK'D	Evgeniia Efimenko		07.05.24				
APPV'D							
MFG							
Q.A				MATERIAL:		DWG NO.	A3
						CDR-002-003	
				WEIGHT:		SCALE:2:1	SHEET 1 OF 1





Note: part to be purchased externally.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	Evgeniia Efimenko		10.04.24		Battery	
CHK'D	Evgeniia Efimenko		07.05.24			
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. CDR-002-007	A3
				WEIGHT:	SCALE:2:1	SHEET 1 OF 1

Appendix 3. FE Analysis of the Cage Drone Robot

Figure 30: Static Simulation of the airframe assembly. Static nodal stress plot.

Figure 31: Static simulation of the airframe assembly. Static strain plot.

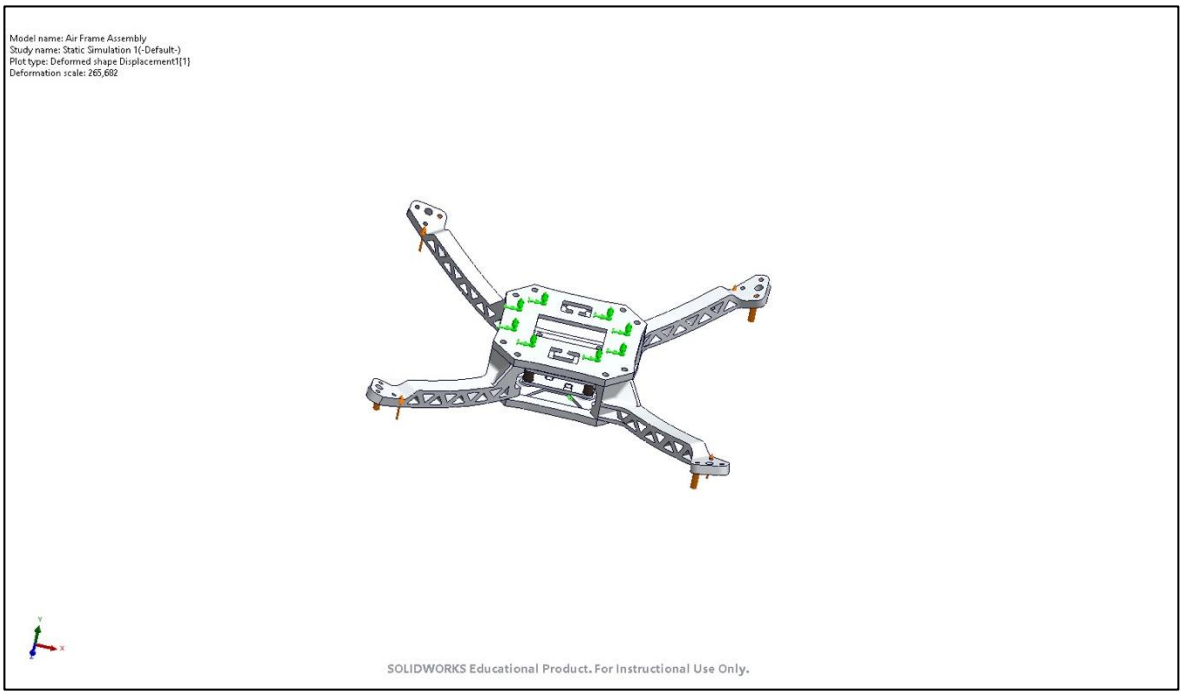


Figure 32: Static simulation of the airframe assembly. Deformed shape displacement plot.

Figure 33: Static simulation of the airframe assembly. Static displacement plot.

Appendix 4. Table of Cage Drone Robot Components

Table 5: Table of Cage Drone Robot Components.

No	Part name	Material	QTY	Identification Group	
1	Spider Base	Aluminium alloy 2024	1	CDR-001	CDR-001-001
2	Spider Top	Aluminium alloy 2024	1		CDR-001-002
3	Spider arm	Aluminium alloy 2024	4		CDR-001-003
4	Fan	Aluminium alloy 2024	4		CDR-001-004
5	Spinner	Carbon steel	4	CDR-002	CDR-002-001
6	Spacer	Aluminium alloy 2024	4		CDR-002-002
7	Electrical Connector	N/A	1		CDR-002-003
8	Pillar	Carbon steel	4		CDR-002-004
9	Distribution Board	Copper (L)	1		CDR-002-005
10	Motor	N/A	4		CDR-002-006
11	Battery	N/A	1		CDR-002-007
12	Electrical Unit 1	Copper (L)	1		CDR-002-008
13	Electrical Unit 2	Copper (L)	1		CDR-002-009
14	Cage	Nylon 6	1	CDR-003	
15	Connecting rod	Carbon steel	2	CDR-004	