

# Master Thesis

For attainment of the academic degree of

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Conception and development of a universal, cost-efficient  
and unmanned rescue aerial vehicle.

Titel (German):

Konzeption und Entwicklung einer universellen, kosteneffizienten und unbemannten Flugrettungsplattform.

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## Abstract

To this day, charities have not been able to provide individual help for people in need. The aim of the thesis was to develop and construct a universal aerial transporter which could be used to support charities in disaster scenarios. The focus was on the technical development based on the results of a feasibility study. The main requirements for the development were in particular: the lowest possible cost for acquisition and maintenance, providing an easy way of reproduction and the ability to control the system using mobile devices. The legal aspects and the collision avoidance were given less priority or were not considered.

In order to identify the current capabilities of charities and their actual problems, a survey among different organisations was done. The results suggested the need for a transport solution. As suitable transport solutions already exist for goods of a mass of at least 50 kg and a transport distance of not less than 100 km, this thesis focuses on the development of a solution below that range and mass.

Various other research works were considered, and it became obvious that most of the research was not concerned with the individual support in rescue operations. These findings were used to gather the requirements for the solution.

Subsequently, a market research was carried out and possible solutions were compared. As it became apparent that there was no suitable solution available, it was decided to develop a new aerial vehicle. To this end every part that was needed and suitable was individually compared and selected. After the transport vehicle had been developed, the system was built. Parts which were not available, especially for the frame and the universal mounting system, were also developed and produced. In order to increase the flight time of the vehicle, materials of a very low mass were used.

During the project a prototype of a universal and unmanned aerial vehicle was successfully developed and constructed. For the transport of different types of goods two different types of universal payload mounting systems were designed. The latter was capable of holding goods with a mass of up to 5 kg. The system allows control of the vehicle in a very convenient way using a mobile device like a smartphone or a tablet. No regular remote control was needed, though still being supported by the system. By



means of an android application missions could be created and transmitted wirelessly to the vehicle. After the transmission the system performed the mission autonomously.

Due to an insufficient stiffness of the frame, a longer flight test is still outstanding. The automatic release of the payload at the destination required an adjustment of the used application or at least a regular radio control in range. The servo motors used for the mounting system tended to yaw their arms and also required a permanent power supply. Further developments should review the use of alternative motors for the mounting system.

## Abstract

Hilfsorganisationen waren bisher nicht in der Lage, Menschen in Notsituationen individuell zu helfen. Das Ziel der Arbeit war daher, die Entwicklung und den Bau eines universellen Flugsystems zum Transport von Lasten, welches in der Lage ist, Hilfsorganisationen in Katastrophenszenarien zu unterstützen. Der Fokus lag dabei auf der Entwicklung einer technischen Lösung in Anlehnung an eine Machbarkeitsstudie. Bei der Entwicklung wurde vor allen Dingen auf möglichst niedrige Anschaffungs- und Wartungskosten, eine leichte Reproduzierbarkeit und die Möglichkeit einer sehr einfachen Steuerung geachtet. Rechtliche und Zulassungsaspekte wurden nur am Rande berücksichtigt. Ein System zur Kollisionsverhütung war nicht Bestandteil der Arbeit.

Um herauszufinden, was die aktuellen Möglichkeiten und Probleme von Hilfsorganisationen sind, wurde eine Umfrage unter vielen großen Hilfsorganisationen durchgeführt. Diese sorgte dafür, dass sich die Notwendigkeit einer Transportlösung herauskristallisierte. Da die aktuelle Versorgung mit Gütern ab 50 kg und über eine Distanz von 100 km bereits sehr gut funktioniert, wurde der Fokus auf die Entwicklung einer Transportlösung unterhalb dieses Bereichs konzentriert.

Viele sehr interessante Forschungsarbeiten wurden im Rahmen der Arbeit studiert, führten jedoch zu der Erkenntnis, dass sich die meisten Forschungsarbeiten nicht mit der individuellen Versorgung von Personen in Not beschäftigen. Anschließend wurden aus den gewonnenen Erkenntnissen die Anforderungen für die zu entwickelnde Lösung zusammengetragen.

Um die Möglichkeit zur Nutzung einer bestehenden Lösung zu überprüfen, wurde eine Marktrecherche durchgeführt und mögliche Systeme miteinander verglichen. Dies führte zu der Erkenntnis, dass aktuell keine fertige und geeignete Lösung existiert und eine neue entwickelt und gebaut werden musste. Dafür wurden alle benötigten Teile mit aktuell verfügbaren und geeignet scheinenden Teilen verglichen und daraus ein System entwickelt. Teile, welche nicht beschaffbar waren, wurden ebenfalls neu entwickelt und selbst hergestellt. Um eine möglichst lange Flugzeit des Fluggeräts zu erreichen, wurde bei der Entwicklung ein Fokus auf die Verwendung von Leichtbaumaterialien gelegt.

Während der Arbeit gelang es, einen Prototyp einer universellen und unbemannten Flugplattform zu entwickeln und zu bauen. Für den Transport von verschiedenartigen Gütern wurden zwei universelle Haltesysteme entwickelt. Letztere waren in der Lage, Lasten bis zu 5 kg zu tragen. Darüber hinaus ermöglichte das System eine sehr einfache Steuerung mittels mobilen Endgeräts, wie zum Beispiel eines Tablets oder eines Smartphones. Eine konventionelle Fernsteuerung wurde nicht mehr zwingend benötigt, jedoch weiterhin vom System unterstützt. Mittels einer Android-Anwendung konnten Missionen angelegt und kabellos zur Flugplattform übertragen werden. Nach Abschluss der Übertragung führt diese den Auftrag umgehend automatisch und autonom aus.

Aufgrund einer unzureichenden Steifigkeit des entwickelten Rahmens stehen umfangreichere Flugtests der Plattform aktuell noch aus. Das automatische Ausklinken der Nutzlast erfordert momentan eine Anpassung der Anwendung auf dem mobilen Endgerät oder zumindest eine Fernsteuerung in Reichweite der Flugplattform. Die verwendeten Servomotoren neigten dazu, sich aufzuschaukeln, und zusätzlich benötigt ein derart aufgebautes System permanent Energie. Zukünftige Entwicklungen sollten daher die Eignung von alternativen Motoren für das Haltesystem überprüfen.

## 1. Introduction

Saving another human being is the ultimate goal for every existing rescue service or aid organisation. Unfortunately, many rescue operations fail or cannot be carried out due to very high barriers. This raised the question for the reason of the failure. The shortfall in funding can be cited as the main reason. However, a lot of the problems rescue organisations are faced with are of a technical nature, which means in many cases there should be a solution to the problems, at least theoretically. Unfortunately, development in this area is not fostered to the extent that is necessary due to missing or not sufficiently conducted research.

On the road to the specific aim of this thesis, a series of current problems that charities are currently faced with was gathered and compared. Following this, the cardinal problem had to be identified.

Apparently, the most important problem area – with the possibility of technical feasibility – would be now the basis for this thesis: the individual or high risk transport of medical equipment in at least difficult terrains. At the moment transports of this kind are too difficult, too inefficient or highly cost intensive – e.g. the transport of sick people in a village in the third world. Another scenario would be that of an environmental disaster. Because of the weather in the rainy season, sending help is not possible, neither via helicopter, because it is much too expensive, nor via truck as the streets have been flooded or damaged. How is it possible to send the people the urgent needed help without putting lives at risk?

In common cases it is not a great distance which has to be covered at the final stage. Most of the medicine is not very heavy; therefore, the mass which has to be transported should not be too big. The main reason why aid organisations are currently not able to provide assistance in such cases, is that the cost-benefit relationship is not as good as it should be. Therefore, they might decide to invest the money donated in aid projects which are more promising and where it is easier to help a large number of people in the easiest way possible.

Another reason could be that well-trained staff is needed for this kind of special jobs or its deployment seems more efficient at another place or in another job. If it was

possible to help these people in need with a low-cost and easy-to-use transport option, charities would not need to spend a lot of time, a lot of funds or employ well-trained staff. This would enable them to help more people with much less effort. The challenge lies in finding the simplest and most cost-effective solution to achieve this goal.

The objectives of this work were in particular: the question of the possibility to support rescue missions with an unmanned vehicle (i), a plausibility check on a technical transport solution by means of a market analysis and if possible of the technical requirements for that tasks (ii) and the planning and construction of a vehicle, taking account of performance, economic aspects (low acquisition and maintenance costs) and maintainability (iii).

In order to achieve these objectives this thesis was divided into sections: the first focusses on the general conditions, the next deals with the development followed by the construction section. The last sections focus on the test of the system. The thesis is then concluded by a discussion and a review.

### 1.1. Survey

In the beginning a market research on the special needs of aid organisations was carried out. In order to gain the information a questionnaire was sent to 22 big aid organisations (see Annex I). The questionnaire contained questions regarding the current situation of aid organisations, their special needs and rescue tasks that actually cannot be carried out. The questions were put into the context of a solution that should take over the task of an individual support, such as an unmanned transport vehicle. Unfortunately, most of the agencies did not answer the questions. When they did, in some cases the wrong person answered them or the contacted person was not able to imagine this area of application. This was of little surprise as there are currently no use-cases for these means of transport owing to the fact that an individual delivery has not been possible so far.

When the request was forwarded to the right person, the response was much more detailed and helpful. The Technisches Hilfswerk (THW) answered the questions in great detail. Strictly speaking, they are already running a feasibility study for autonomous aircraft delivery. In another research project, they try to document the flow of large groups of people. This answer was not surprising, because the civil usage of unmanned aerial vehicles (UAV) has risen rapidly over the last years [1]. Another aid agency reported that they often deliver medical material from 50 kg to 50 t using big trucks. With the commitment that aid agencies want to improve the access to new transport facilities, it seems that an additional type of vehicle is what they need most. At present, charities use trucks on site to transport and distribute humanitarian aid. As a result, the vehicle should be able to transport goods within a range of 100 km and a payload of 50 kg and below, because that range is not covered at the moment. Another reason is the advantage of portability which correlates with the dimensions of the vehicle.

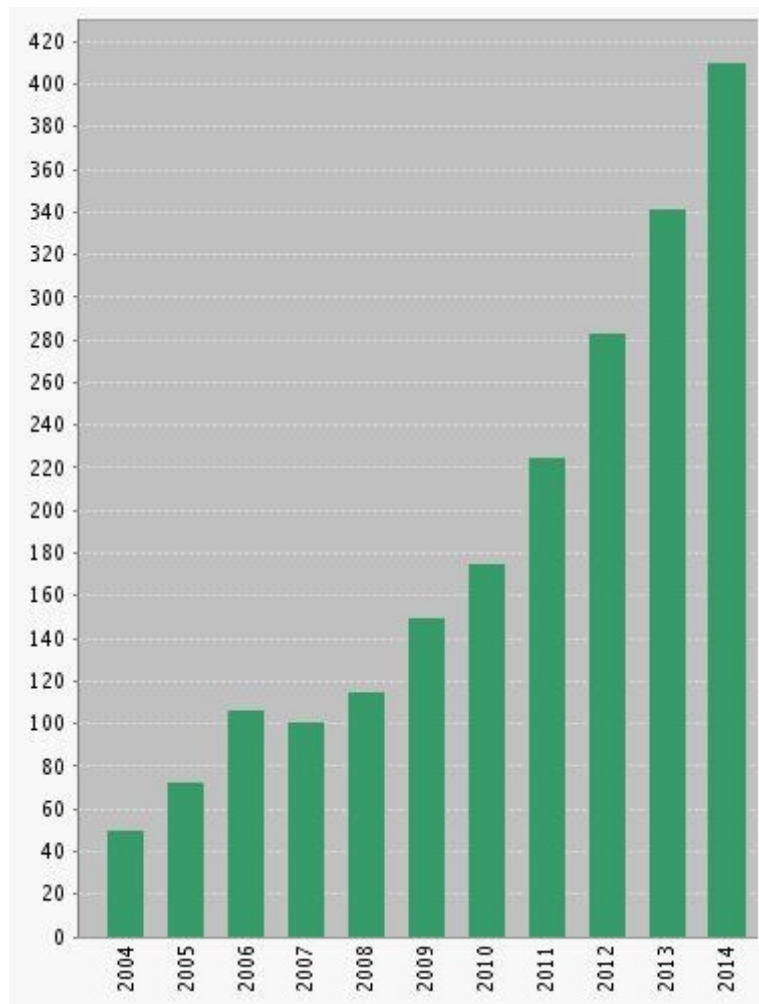
To identify the type of vehicle that is needed most and which would best improve the support, a few options were compared. There obviously is no need to transport aid supplies by road as this already works very well for most types of ranges. The transport by water was unsuitable, because it is not reasonable to assume that lakes,

rivers or oceans are available on site. Since both other ways of transport have dropped out, the only suitable way to transport goods seems to be by air.

Based on the reduced transport mass and the objective of a low-cost solution, a manned vehicle is not suitable. Therefore, the vehicle should be an unmanned aerial vehicle.

## 1.2. Scientific Development

Currently, the topic of rescue operations has been taken up in different technical projects and scientific papers. The increasing number of the publications shows the growing importance of this topic [2]. Figure 1 below shows the published items for the term UAV over the past ten years. The enormous increase of the yearly number of publications at the WEB OF SCIENCE (T. Reuters WWW.) since 2004 illustrates the increasing interest in this topic in various subject areas.



*Formula 1-1: Number of publications with the Keyword UAV over the past ten years [2].*

Perhaps the latest and best-known example is the experimental UAV system for search and rescue [3]. The study by Erdos et al. addresses the performance of the developed avionic systems. The researching team reached the limit of the technically feasible with regard to the wireless link and with the image processing in particular. On these grounds, the developed system should be independent of wireless links and be able to navigate on its own. It needs to be considered that the navigation should not depend



on a visual-based system following from the fact that an optical system could be interfered by various sources. It became obvious that the system contained many factors of an experimental craft.

Another study by D'Souza et al. focussed on Blimps as a type of aircraft. In the specific case, they tried to implement an internet platform in the aircraft [4]. This could be used to set up a wireless network with internet connection in disaster scenarios.

The current state of research has already made the transition from unmanned aerial vehicles to autonomous aerial vehicles (AAV). Currently, there are miscellaneous projects by research facilities developing autonomous aircrafts which are able to navigate with optical or infra-red sensors without GPS, or indoor. A few projects have focused on the flying of mini UAVs in a swarm. There are projects dealing with the autonomous handling of different tasks, such as the research around Hauert et al. that developed fixed wing UAVs which orient themselves like birds in a swarm [5]. Another study was by Kushleyev et al. from the University of Pennsylvania which was concerned with the development of nano quadcopter robots [6].

Other research teams have focused on optical flow based autopilots with speed control and obstacle avoidance of UAVs, such as the team around Franceschini, Ruffier and Serres [7]. They did research on a collision avoidance system with optical flow sensors. The system was based on the principles underlying elementary motion detectors in flies, using a single neuron recording and single photoreceptor stimulation.

In summary one can say that this area is in a radical change.

### 1.3. Requirements

To avoid the problem of a missing site for take-off and landing, the type of aerial vehicle should be a multi-rotor rotation wing construction. Therefore, a fixed-wing aeroplane construction was not an option.

In order to identify the features required, a requirement engineering was conducted. The aim was to transport urgently needed goods from one place to another. The maximum payload for a rotary-wing aircraft was set to 5 kg to allow a maximum range of 30 km as well. This was due to a lower range and a lower flight time, respectively, resulting from the higher load of the motors and therefore a higher burden of the accumulator. It was assumed, that a copter with a payload of 5 kg would need standard motors that are readily available and not require as much energy to accomplish the mentioned flight range<sup>1</sup>.

In order to allow mounting of any good on the aircraft, it was also necessary to develop a universal mounting system. To accomplish the target of 5 kg payload it was essential to use very efficient engines, very light mass materials and a battery of a very high capacity. To simplify the authorisation of the UAV in Germany, it was planned to preferably set the lowest take-off mass (TOW) below 5 kg [8]. This limit was set, because a UAV with over 5 kg TOW needs a separate rising permission for every start [9]. This would be very expensive and unpractical for an operation in Germany. For a usage abroad this limit was less important, as there are no such high security and aeronautical regulations.

With an assumed TOW of 5 kg for the UAV without any payload and also a maximum payload of 5 kg, the aircraft has a maximum TOW of 10 kg with load. To ensure reasonable flight characteristics it is advisable to have an excess thrust ratio of at least two to one<sup>2</sup>. To implement this ratio, the UAV should have a thrust of about 200 N. The

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<sup>1</sup> A more detailed calculation of the flight time and the load was done when the configuration of the used parts was clear. See chapter 2.1 Copter Development.

<sup>2</sup> This ratio reflects the general opinion of the scientific staff of the faculty of Aeronautical Engineering of the TH Wildau and of third party experts.

last, and one of the most important requirements, is a high level of resistance against environmental influences. These include very high or low temperatures, precipitations, snow or sleet, and wind. As a result, a fully protected frame and enclosure for the electronics and the batteries and, corresponding with that, a suitable motor was required.

As Demska and Grzejszczak noted in their studies on computational intelligence in 2013: by means of an organised system network architecture it would be possible to control the UAV using multiple platforms [10]. The feature of multi-access to the UAV allows to set up a connection easily and, above that, provides a failure safety feature. When one connection type fails, another would be ready to assume the control. Therefore, the system should be able to receive control commands in a classical way via Remote Control (RC) transmitter or in a modern way, using remote access via the Internet or a mobile device.

To avoid overextending the users of the UAV, it should be very easy to use. At best, it should be possible to use it without a long time of training. Taking that into account, there should be the option to control the whole system using a mobile device, such as a notebook, a smartphone or a tablet. Moreover, the UAV should be able to receive a whole mission. Such a mission might look as follows:

- take off,
- fly to GPS coordinate (latitude and longitude),
- do something,
- fly to start point and
- land.

According to the remarks of Wendel, a failure in the system which determines the position and the location could eventuate in a crash [11]. To avoid these types of accidents it would be an asset if the UAV had different stability and navigation systems on board. To be precise, the system should have at least a GPS navigation system (GPS), a pressure altimeter and different micro electro-mechanical systems. The use of these components will confine the risk of a crash.

## 1.4. Market Research

There are many different types of UAVs (colloquially called “drones”) on the market. Therefore, the first questions which had to be answered were: which type of aerial vehicle should be used and is it possible to use an existing UAV? Or would it be necessary to build a new one? Before the UAV could be built, the named requirements had to be verified.

At the moment of writing of the thesis, there are a few professional UAVs on the market. In order to examine the possibility of using any of these products, the UAVs of the three biggest companies were reviewed in terms of their suitability for the project’s needs.

Currently, DJI, microdrones and Schiebel are three major manufacturers of civil UAVs.

DJI says about themselves, that they are “a privately owned and operated company [...] DJI focuses on our own vision, supporting creative, commercial, and non-profit applications of our technology” [12].

At present, DJI’s largest multicopter is the Spreading Wings S1000+, which has the opportunity to take a maximum payload of 9.5 kg on a windless day [13]. The Octa-Copter<sup>3</sup> is a highly portable air vehicle owing to its foldable arms. The possible flying time with a built-in 15 Ah lithium-ion polymer accumulator (LiPo) is up to 15 minutes. However, the copter is not waterproof. The price of the octocopter, provided by a German supplier, was at around 1,900.00 EUR at the beginning of April 2015. Delivery time is unknown. The provided Copter does not come with any Flight Control (FC), LiPo or Gimbal, nor is a ready-to-fly (RTF) kit available. The missing parts, including the frame, would cost around 3,500.00 EUR<sup>4</sup> without VAT. A final assembly with fine-tuning is estimated at around 1,500.00 EUR.

The company microdrones already built a working transport UAV in cooperation with the DHL Deutsche Post [14]. For that intention they used the md4-1000 flying platform.

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<sup>3</sup> An Octa-Copter is defined as a multi-rotor UAV with eight arms, motors and rotors.

<sup>4</sup> A suitable FC is about 850.00 EUR [88], one LiPo accumulator is priced at around 400.00 EUR [89].

This quadcopter allows a flight time of up to 88 minutes or, alternatively, a payload of 1.2 kg. Rain, snow or dust should be no particular problem. The maximum operation height is 1,000 meters and the flying range is at least 500 m using a remote control. [15]. Autonomous flying is not possible. The md4-1000 has a pricing of at least 40,000.00 EUR [16]. A universal payload mounting system is not offered [17].

The Camcopter S-100 is the biggest flying platform by Schiebel. The company started using UAVs for mine detection in the 1980s. In 2006 they started the serial production of autonomous civil, maritime and military drones.

The *Camcopter S-100* allows a fully autonomous flight with a payload of up to 50 kg and a range from 80 km to 180 km [18]. It has different safety systems on board, including global positioning system and a GLONASS receiver, a redundant inertial measurement unit (IMU) and an intelligent power supply. A system consisting of one ground control and two S-100 is about 2,000,000.00 EUR [19].

In comparison of these three different models, it was found that there are powerful flight systems on the market. However, the technical specifications as well as the costs for the system are far removed from the project's requirements. As a result, it was decided to develop a new copter that would allow accomplishing the specified objectives.

### 1.5. Legal Aspects

Besides the technical problem, there are further issues: the ethical and legal aspects of unmanned systems. The mere fact of the negative association of the word drone makes it more difficult to build and develop this type of transport vehicle. People's fears regarding the drones are very comprehensible. Drones have the image of being monitoring and killing robots. As Canning and Dabringer wrote in their book 'Ethical and legal aspects of unmanned systems', a robot does not know suffering, injuries, or death [20]. UAVs could be used to monitor citizens and will develop a high destruction potential due to their mass in the event of a crash or a rigid impact. Robots can be damaged or destroyed. However, they can, if damaged, be fixed, or if destroyed, be replaced. On the other hand, these scaring characteristics offer a great advantage that allows sending a UAV on a rescue mission into high risk terrains without risking a human life. At present, it is impossible to predict whether or not the support UAVs will be accepted by the general public.

Permissions for take-off can vary widely, depending on the take-off mass, the location and, above all, the local legal aspects. The latter can vary strongly. Especially today, with the advent of small and micro UAVs, many legislative initiatives have changed the conditions for the usage of UAVs.

In the recent past, the Deutsche Flugsicherung (DFS) has relaxed the terms for take-off permissions in Berlin, primarily for light mass UAVs of up to 5 kg [21]. This was due to the increasing amount of requests to the DFS in the past. Rising permissions are also strongly regulated, but now every small UAV that flies within a height of 30 m and outside of the Berlin S-Bahn ring keeping a distance of more than 1.5 km to airports generally receives the clearance for take-off.

In general, UAVs below a TOW of 5 kg need insurance and the authorisation of the owner of the property [8, 22, 23]. In the weight class of up to 25 kg a separate rising permission is needed [24]. For TOWs of above 25 kg a large number of regulations apply [24]. Most of them deal with individual decisions for special flight properties. Therefore, a general statement for the rising permission of aircrafts of over 25 kg could not be made.

Generally, aircrafts have very high requirements concerning the safeguarding against failure.

In addition, there are many restrictions for the commercial usage of aerial vehicles which are intended for the application of autonomous support near people.

It can be reasonably assumed that the planned UAV has a TOW without payload of around 5 kg. With payload the TOW approximately increases to 10 kg, therefore the UAV can be most likely assigned to the class of aircrafts of up to 25 kg.

In order to bypass most of these restrictions, it was decided to develop the UAV exactly for the purpose originally intended: the deployment in the event of catastrophes. It was, however, considered that in disaster scenarios and in third world countries the legal requirements regarding failure safety would be less strict or there would be no restrictions at all. Also, charities will probably have special authorisations to rise with a UAV. Therefore, most of the restrictions for using a UAV would not apply.

## 2. Development

### 2.1. Copter Development

Based on the results of the introduction, it was necessary to research, develop and build a partly autonomous working UAV. In the planning phase attempts to realise a maximum payload of 5 kg were made. In a later version it would be conceivable to increase the net load up to 10 kg. To make sure that the workforce of the aid groups does not have to undergo a lot of training in order to deploy the UAV, it should be possible to enter the mission's data easily. The plan was to allow to control the UAV using a smartphone or a tablet. Finally, the UAV should be able to hold and deliver almost every object with a determined size within a range of 30 km<sup>5</sup>.

#### 2.1.1. Aircraft Type

First of all, the type of rotary wing aircraft was to be chosen. The choice was between a single-rotor and a multi-rotor design. Single- and multi-rotor systems show great differences regarding maximum thrust, stability, safety and other properties. A single main rotor helicopter is usually bigger than a multi rotor UAV providing better handling in windy conditions [25]. In relation to the size it is able to take more payload owing to the increasing size of the rotors and therefore a larger lifting surface. In the following example the surface of a 12 inch<sup>6</sup> hex copter is compared to a standard 1,400 mm single rotor helicopter:

$$A = \pi * r^2$$

*Formula 2-1: Circular surface*

Based on the formula 2-1, the calculation for the lifting surface for both variants is shown in formula 2-2 and 2-3:

$$A = 6pcs \left( \pi * \left( \frac{30.48 \text{ cm}}{2} \right)^2 \right) = 6 * 729.658 \dots \approx 4,377 \text{ cm}^2$$

*Formula 2-2: Lift surface calculation for a six-rotor-multicopter*

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<sup>5</sup> Point of no return (PONR).

<sup>6</sup> 12 inch corresponds to 30.48 cm.



$$A = \pi * \left( \frac{140 \text{ cm}}{2} \right)^2 \approx 15,394 \text{ cm}^2$$

*Formula 2-3: Lift surface calculation for a standard single rotor helicopter*

The calculation shows that two flight systems with almost the same dimensions of the boom have highly different properties. In the example given, the single rotor helicopter would have a lift surface approximately 352 % higher than a six rotor multi copter. The single rotor is also able to auto-rotate down in case of an emergency. On the other hand, the procedure of vibration frequency tuning is more complex and the copter is more difficult to fly [26]. A multi-rotor design has the advantages of very easy flying conditions, a simple vibration tuning (higher frequencies) and smaller machines [27, 28]. The disadvantages include the missing autorotation feature, which results in a crash when one motor quits<sup>7</sup> or when the FC or other electronics are defective [29]. On top of that, the appearance of the copter is less intimidating, making it still dangerous though. It has a lower payload and less efficiency – in comparison with a single main rotor helicopter [30]. From the neutral and factual information one can assume that the single-rotor system is the better option, but unfortunately there were no FCs on the market suitable for a single-rotor design copter of the required size with an auto-pilot and several gyroscopes<sup>8</sup>. Despite the variations in technical features of the different types of copter designs, there is no other option than the multi-rotor UAV.

A multi-rotor aerial vehicle permits different frame erection variants. The three types – Quad-, Hexa- or the Octo-copter – are probably the most popular and best-known. A conceptual drawing of a Quad-X copter is shown in figure 2-1:

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<sup>7</sup> This concerns anything less than a copter with eight (octo-copter) respectively six (Y6-Copter) motors.

<sup>8</sup> There was one single rotor with an experimental autopilot available, but it was recommended to use it only for rotors up to the size of 700 mm [101] which would be based on the Pixhawk FC. A rotor with this size would not be sufficient for the planned system, because it would not provide enough thrust. More information on the required thrust is given in the description of the motor-prop thrust at a later point in this chapter.

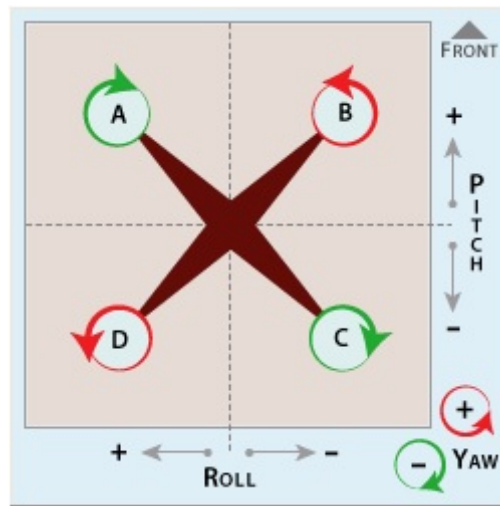


Figure 2-1: Conceptual Drawing of a Quad-X copter (screenshot QGroundControl)

The named types are equipped with four, six and eight brushless motors, respectively. Each of the mentioned types allows additional models, e.g. in the form of a +, an X, an H or a V. On top of this, it is possible to mount two motors with opposite rotation direction at each mounting position. Among the frame variation the power of the motor and the size of the rotors affect the flight properties and the thrust significantly.

In general, it can be predicted that the more motors an UAV has, the better the flight characteristics. In fact, the opposite applies for flight time and mass. The more motors are mounted the higher the mass of the UAV and the less flight time is available<sup>9</sup>. Furthermore, the costs increase substantially. To achieve the longest flight time and – if possible – a favourable price, the use of a large quad-copter<sup>10</sup> turned out to be the best solution.

### 2.1.2. Flight Control

It was then required to choose the core of the UAV, the FC. During this phase potential FCs were compared. The most popular and suitable FCs were the Wookong (DJI), the AutoQuad, and the Pixhawk [31].

<sup>9</sup> Assumed the environment variables are still the same.

<sup>10</sup> Obviously concerning the power, not necessarily the whole dimensions of the UAV.

The DJI Wookong is a flight controller, which allows a smooth cinema flight. It is easy to fly and offers many features, such as intelligent-orientation-control and return-to-home [32]. This makes it a perfect choice for beginners or cinematographers who do not want to worry about how to fly perfectly in order to get the shot they want. The major disadvantage of the Wookong FC is that the firmware cannot be modified in any way, so no extensions or extra features can be added unless DJI releases a firmware update.

The second flight controller under review, the Pixhawk, is a Linux Foundation DroneCode project. The flight controller has been specifically designed for autonomous flying [33]. The Pixhawk provides more features than the Wookong FC, but more importantly, comes with a software and firmware by 3D robotics that is open-source. This enables the user to make any necessary modification and addition making the Pixhawk a useful tool for advanced research projects.

The other options so far can be considered good flight controllers, but none of them has very good flight characteristics. Here the AutoQuad proves to be a better choice. There are a few other flight controllers on the market – like the Wookong – which are easier to setup and fly, but the flight quality of an AutoQuad is unmatched [34]. Provided that a complex configuration would not present a problem, the AutoQuad produces good results making it superior to all the other systems.

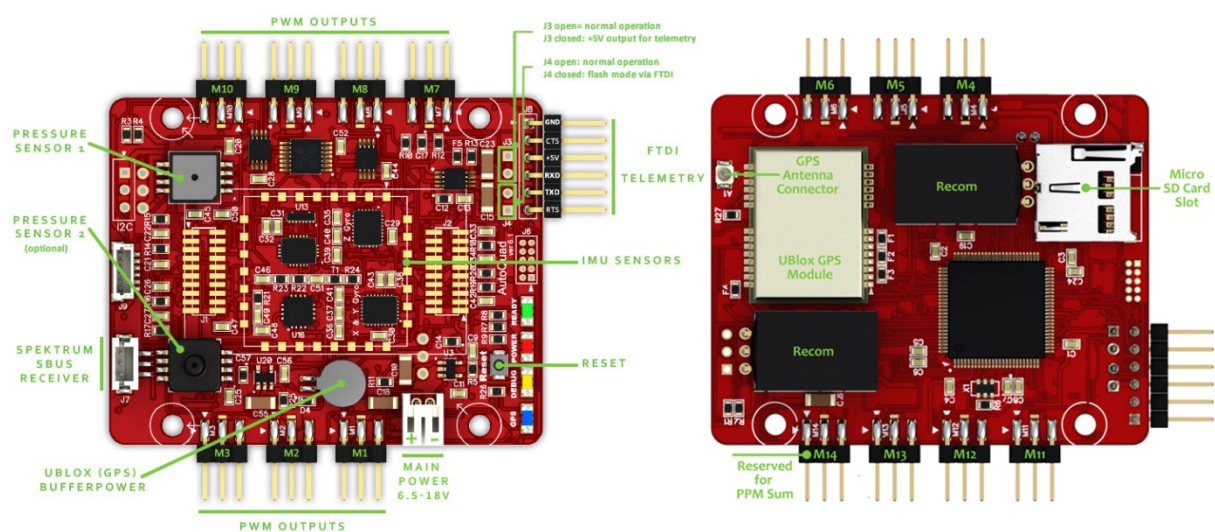


Figure 2-2: Rendered image of both sides of the AQ6 Board (based on AutoQuad.org [35])

In the case of the Best Easy-to-use Arial Support Transporter (BEAST)<sup>11</sup>, the focus is on flight quality. The AutoQuad FC is partly open source, highly functional and provides the subjective best flying performances [34]. As shown in figure 2-2, the board provides many extension ports which allow an easy extending of the board. Therefore, in this comparison the decision was in favour of the AutoQuad.

### 2.1.3. Electronic Speed Control

Based on the AutoQuad FC the best electronic speed controller (ESC) suitable for the project was the AutoQuad ESC32. The main advantage of using an ESC32 is, that it allows transmitting telemetry data to the FC and the radio control (RC) [36]. In addition to that, there is reason to believe that the FC and the ESC work best together when they are from the same manufacturer. The disadvantages of the AutoQuad ESC32 are, that it is comparatively expensive<sup>12</sup> and only supports up to five cell lithium-ion polymer batteries (LiPo) in version 2<sup>13</sup> [36]. A five cell LiPo supports a voltage of around 18.5 V<sup>14</sup>. The maximum (max.) continuous current is at about 50 A (cooled) or at around 25 A (uncooled) [37]. To ensure that the ESCs work well, it was necessary to solder at least one capacitor directly onto the ESC, as shown in figure 2-3.

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<sup>11</sup> This was the internal codename for the project.

<sup>12</sup> Each AutoQuad ESC32 v2 is about 39.90 EUR.

<sup>13</sup> This was the current version during the writing of this paper.

<sup>14</sup> One cell has a voltage of 3.7 V. The series (S) connection of five cells gives 18.5 V (5S).

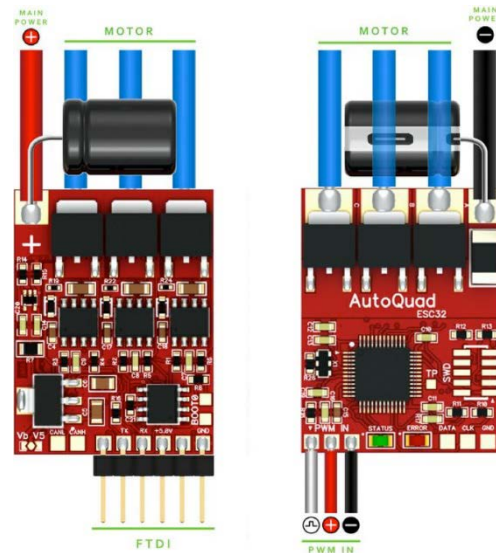


Figure 2-3: AutoQuad ESC32v2 (based on AutoQuad.org [37])

An alternative to the AutoQuad ESC32 could be the T-Motor Air 40 A. It supports two to six cell LiPos [38]. The maximum current is at 40 A continuous or 60 A in peak. Because there was no need for further ESC comparisons the ESC32 for AutoQuad was chosen.

#### 2.1.4. Motor

To achieve the aim of a 5 kg payload, the key component, besides the FC, is the brushless motor. The most powerful motors are supplied by Plettenberg and T-Motor.

Most Plettenberg motors have a large output reserve and are of a high quality [39]. Disadvantages include, that they are usually very heavy, expensive and often require at least eight cell LiPos [39, 40, 41]. The Xtra 25 Evo is a brushless external rotor motor optimized for flights [41]. At 8S they provide a maximum thrust of 60.8 N (Xtra 25 / 12 Evo with RASA 20-inch x 10-inch airscrew). The motor has a mass of 520 g. The list price of the Plettenberg motor is currently at 454.00 EUR.

Very professional alternatives to the mentioned motors are the T-Motor engines. Especially the features of the U8 Pro series are remarkable. The manufacturer authenticates that the motors are of a light mass, powerful and water as well as dust resistant [42]. The motors work well from 6S to 12S, they have a maximum thrust of up to 49.2 N (KV170 by 6S with 29 inch \* 9.5-inch carbon fibre airscrews) and an efficiency of 0.093N/W [42]. Furthermore, with only 239 g the motors are very light. The current



catalogue price is 299.90 USD.<sup>15</sup> The U8 Pro provides a very special feature. As shown in figure 2-4 the motor is fully covered enabling it to also to perform in rain and snow due to its enhanced water protection.



*Figure 2-4: T-Motor U8 PRO 170KV (own representation)*

A comparison of these two motors shows that the T-Motor on the one hand has a maximum thrust that is around 19 % lower, but on the other hand has a price and a weight of approximately 41 % and 54 % lower, respectively. Furthermore, the availability of the Plettenberg motor is good in Germany, but when the copter is to be used worldwide delivery problems could arise. T-Motor, on the other hand has a great number of distributors around the world, ensuring a supply of replacement parts.

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<sup>15</sup> At the time of writing, this corresponds to an exchange value of around 269.00 EUR.

### 2.1.5. Propeller

As concerns the propeller, it was necessary to choose one that was compatible with the motor. T-Motor provides propellers, which are optimised for their motors. Therefore, it was necessary to select a propeller with suitable specifications. In order to receive the most possible thrust, the choice fell on the 29-inch x 9.5-inch airscrew [43]. As shown in figure 2-5 the propeller is completely made of carbon fibres.



*Figure 2-5: T-Motor Carbon Fibre Prop 29x9.5 (own representation)*

Together with the named motor, this set provided the maximum thrust, as specified above. The highest efficiency of 145 N/W was achieved at a throttle of 50 % [42]. Each propeller has a mass of 104.2 g per blade [43].

### 2.1.6. Possible Problems and Incompatibilities

Together with a light mass frame, the copter could be ready. On closer examination it became evident that the FC and the ESC would not work well with the motor. The problem was that the FC worked with 4S [34], the ESC [36] supported a power supply of up to 5S and the motor needed at least 6S to perform in good conditions [42]. To solve that problem, the RECOM DC/DC-Converter on the FC needed to be replaced. The implemented R-78B5.0-1.5 had a supported input voltage range from 2S to 5S [44]. Through an upgrade to an R-78B5.0-1.0 RECOM [45] it was now possible to use a two to eight cell power supply. However, the upgrade of the ESC32 from AutoQuad proved to be problematic. This was due to the fact that the ESC does not provide a RECOM that is easily exchangeable. The voltage of the ESCs was influenced by the utilised high voltage transistor switches and these cannot simply be replaced. There-

fore, it first was planned to use this combination with 5S. Upon request the manufacturer of the motor certified the feasibility of using the motors with 5S. This would merely result in a slight decrease in efficiency of the engines.<sup>16</sup>

For the occasion that the planned parts would not work well together, a suitable fall back solution needed to be found. This was primarily important for the ESCs and the motor. Therefore, the manufacturer of the motor was requested to recommend a matching light mass speed controller. As a result, the Air 40 A ESC was suggested. These ESCs allowed using a voltage of 6S. An alternative, which was recommended was the use of T-Motor's Flame 80 A ESCs which have double the continuous current of 80A and a peak current of 120 A [46]. They have a CNC aluminium alloy enclosure and an IP55<sup>17</sup> printed circuit board (PCB). With a size of 62 mm x 41 mm x 17 mm (WxHxD) and a mass of 106 g per piece, they have also at least doubled in terms of their size and mass.

#### 2.1.7. Accumulator

To power a UAV with a peak mass of 10 kg a suitable accumulator had to be chosen. For power supplies based on chemically reactions, such as an accumulator, the use of the lithium-ion polymer accumulator (LiPo) technology is well established among experts. This is due to the fact that LiPos have one of the highest energy densities available [47]. Therefore, the comparison of suitable power sources was limited to LiPo accumulators. It was one of the most difficult tasks to find a practical LiPo, the main reason being that the relation between stored energy, mass and resulting flight time cannot be calculated accurately. This was due to the fact that the calculation consisted of many unknown parameters. Nevertheless, to estimate the power demand to provide the required capacity for accumulator a rough calculation was made. It shall be

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<sup>16</sup> The manufacturer certified an efficiency of 90 % to 95 % of the original value.

<sup>17</sup> IP - International Protection. IP55 certifies that this part is completely protected from any objects and only allows dust-sized particles in non-harmful quantities to penetrate. Furthermore, it protects from a low-pressure water jet with a 6.3 mm nozzle. This standard was specified in the IEC 60529 [90].



assumed that the copter needs 50 % of throttle to hover<sup>18</sup>. This results in a power consumption of approximately 133.20 W per motor (mass divided by efficiency) [42]. To realise a flight time of 45 minutes the accumulator should have a capacity of at least 20 Ah<sup>19</sup> for flights without payload. This was calculated as follows:

$$Q = I * t \quad \text{with} \quad P = U * I \quad \rightarrow \quad I = \frac{P}{U}$$

*Formula 2-4: Formula for the electric charge*

$$Q * U = P * t$$

*Formula 2-5: Shifted formula 2-4 of Q*

$$Q = \frac{P}{U} * t$$

*Formula 2-6: Shifted formula 2-5 of Q*

$$Q = \frac{133.2 \text{ W}}{22.2 \text{ V}} * 0.75 \text{ h} = 4.50 \text{ Ah}$$

*Formula 2-7: Calculation of Q (formula 2-6) for one motor*

With: Q = Electric charge (Ah)

I = Current with consistent power (A)

t = Time (h)

P = Electrical power (W)

U = Voltage (V)

At best, the four motors require a capacity of 18 Ah for a flight scenario without payload and a flight time of 45 minutes.

Since it was assumed that the efficiency rapidly decreases with increasing payload, or with other built-in electronics—like servo-motors—or during the performance of complex flying manoeuvres, the required demand was estimated at 25 Ah (6.25 Ah for

<sup>18</sup> With an estimated mass of 6 kg, a throttle of 50 % resulted in a calculated thrust of 19.3N per motor at a calculated efficiency of around 0.145 N thrust per watt [42].

<sup>19</sup> The value is based on the calculation of the formula 2-7.

each motor, see formula 2-8)<sup>20</sup>. This capacity shows the average of payload in the relation to the requested flight time of 45 minutes. With a throttle of 51.8 % one motor should have a thrust of  $\approx 20.6 \text{ N}$ <sup>21</sup> and 185 W of power consumption<sup>22</sup>. With a take-off weight of around 6 kg the UAV should be able to lift a mass of up to 8.3 kg under optimal conditions. This would result in a theoretical maximum payload of 2.3 kg. Of course, this scenario is not realistic and only shows the required power consumption under optimal conditions. It would not be possible to fly with good flying properties in this composition.

$$Q = \frac{185 \text{ W}}{22.2 \text{ V}} * 0.75 \text{ h} = 6.25 \text{ Ah}$$

*Formula 2-8: 2.3 kg payload LiPo capacity calculation based on linear equation of the data sheet for one motor (table 2-1)*

The calculation for the max payload scenario is shown in formula 2-9:

$$Q = \frac{528.36 \text{ W}}{22.2 \text{ V}} * 0.75 \text{ h} = 17.85 \text{ Ah}$$

*Formula 2-9: Max payload LiPo capacity calculation based on the data sheet for one motor (table 2-1)*

In total, this implies a required accumulator capacity of over 70 Ah and this in turn would mean that the copter had a mass of much more than 10 kg. Therefore, a maximum load configuration would entail a shorter flight time. For a setting with a 25 Ah LiPo this would result in a theoretic<sup>23</sup> flight time of approximately 15 minutes (see formula 2-10).

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<sup>20</sup> A maximum payload scenario would result in a LiPo of the following capacity:  $((528.36 \text{ W} * 4 \text{ pcs.} / 22.2 \text{ V}) / 60 \text{ min.}) * 45 \text{ min.} = 71.4 \text{ Ah}$ . Ineffectiveness and additional electronics were not considered.

<sup>21</sup> Calculated values based on the given parameter from T-Motor [42]. The linear equations  $(0.74x + 133.2 = y)$  and  $(7.696x + 133.2 = y)$  based on the given parameters at 65 % and 50 % throttle:  $0.74 * 1.8 + 19.3 = 20.633 \rightarrow 20.6 \text{ N}$  at 51.8 % throttle ( $7.696 * 6.730769231 = 51.8$ ). The linear charts of these parameters can be found in Annex II and Annex III.

<sup>22</sup> Following the linear equation from <sup>21</sup> the following equation could be derived:  $7.696 * 6.730769231 + 133.2 = 185$ . Therefore, the motor has a power consumption of 185 W at 51.8 % throttle.

<sup>23</sup> This value is based on the theoretical calculation in formula 2-9. This value does not represent a realistic flight time, because it is based on a throttle of 100 %.

$$Q = \frac{60 \text{ min.}}{\left( \frac{\left( \frac{528.36 \text{ W} * 4 \text{ Pcs.}}{22.2 \text{ V}} \right)}{25 \text{ A}} \right)} = 15.75 \text{ min.}$$

*Formula 2-10: Calculation of a max payload scenario for four motors*

LiPos with the specifications of 25 Ah and 22.2 V are hardly available on the market.

A research for a reseller of this type of LiPo was only done for Germany as a LiPo of this capacity has a high risk potential and is counted among dangerous goods by shipping companies. On this account, it would be cumbersome to obtain.

As a result, the use of the following LiPos was possible: The first was the Tattu 22,000 mAh LiPo Battery Pack [48]. This LiPo has the dimensions of 195 mm x 91 mm x 64 mm (WxHxD), a net mass of 2,509 g and the internal parallel connection of two 11 Ah 6S batteries. The last property is relevant for the battery's reliability. Currently, the price for this type of LiPo is about 460 EUR.

The second LiPo in this comparison comes from SLS. The SLS APL 21,000 mAh LiPo has a mass of 2,464 g, dimensions of 228 mm x 99 mm x 48 mm (WxHxD) and is of an excellent quality [49]. In May 2015 the price of the provided LiPo was 389 EUR.

The third option was to use one or two 16 Ah LiPos. In this case the PULSE LIPO 16000 mAh would be first choice. It has a mass of 1,920 g and dimensions of 178 mm x 75 mm x 63 mm (WxHxD) [50], and is currently available at a price of 299 EUR.

In comparison of these three possibilities the SLS LiPo has the best ratio of mass, dimensions and price. Therefore, it is the product of choice.

### 2.1.8. Frame

As described above, the copter should have the structure of an X (quad) allowing the construction of a system with only four motors. This benefits the building costs and the mass of the system.

At the beginning of the project it was chosen to use a pre-soldered centre plate set [51]. This allows making a pre-building at the lowest expenses and costs. Due to the pre-

soldering, the plate has an integrated power distribution board (see figure 2-6). The plate allows to control some LEDs directly, e.g. to get a flight status response. However, this prefabricated solution has a number of disadvantages. The centre frame construction has very thin (2 mm) sandwich<sup>24</sup> plates, — a mixture of glass-fibre reinforced plastic (GRP), conductor tracks and colour. These plates have a diameter of just 150 mm. They support 18 mm tubes for the mounting of the motor. All in all, the plate is suitable for development and testing, but not for a productive flight scenario.

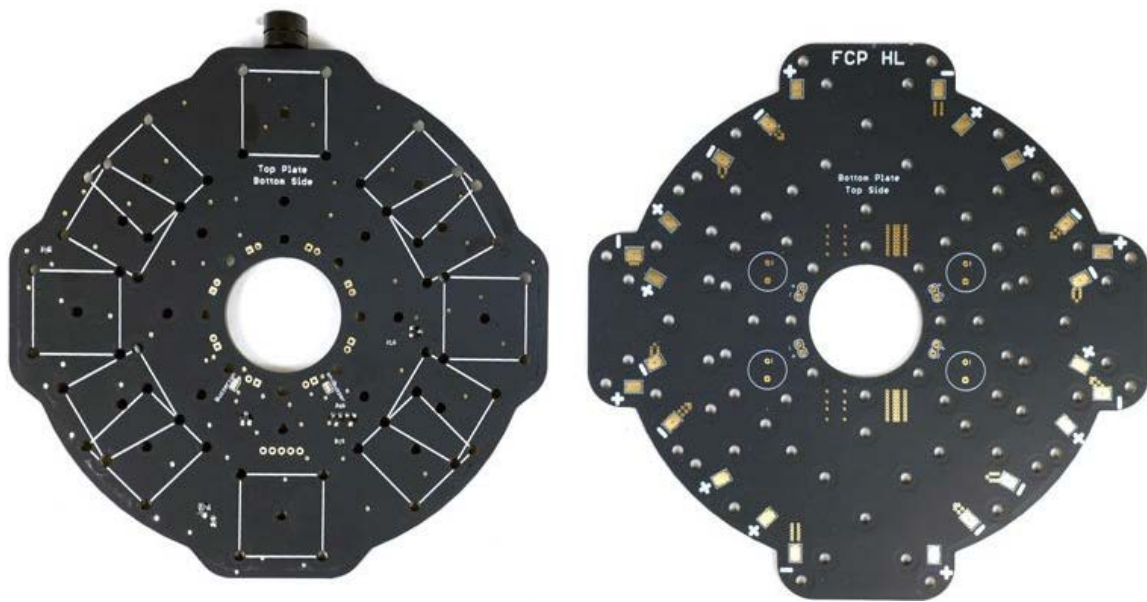


Figure 2-6: Pre-soldered centre plate for the test frame (based on flyduino.org [51]).

Following the test construction, a stronger board with thicker plates and a larger diameter, a separate power distribution board, larger tubes and more fixation points should be set up.

The length of the tubes depends on the size of the rotor blades. As calculated, a rotor with a size of 29.5 inch provides the best performance. Accordingly, the tubes have to be of a size that on the one hand avoids contact between the rotors and on the other hand provides the best flight performance possible and an optimal level of noise. Given that carbon tubes are only available with a length of 1 m and above, the decision

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<sup>24</sup> In contrast to a sandwich-structured composite, the provided and used sandwich construction was realised through the two centre plates, which should be mounted one above the other leaving some space for the tubes and some locking points between them.

was made to use the 1 m tubes first, which would be cut to the correct length after the testing phase was completed.

### *Vibration Calculation*

In order to avoid strong vibrations generated from the motor which could cause amplifying, the mass on the tip of the arm was compared to the possible length and the wall thickness of the tube of the copter's arm. The following formula reveals the strength of the current vibrations and any potential mutual influences [52]:

$$f = \frac{\sqrt{\frac{3EI}{L^3M}}}{2\pi}$$

*Formula 2-11: Natural frequency of a cantilever beam with a mass on the tip.*

With: L = arm length (mm)

M = mass (kg) on tip (motor + brackets + bolts)

I = moment of inertia ( $I_x = \frac{\pi(d_o^4 - d_i^4)}{64}$ ) with

$d_o$  = cylinder outside diameter (mm) and

$d_i$  = cylinder inside diameter (mm)

f = frequency in Hz

E = a real value to compute the natural frequency of a copter in MPa

The interesting element in this formula is the E. E stands for the Young's modulus. The Young's modulus is a measuring parameter that is used to quantify the stiffness of an elastic material [53]. Therefore, the formula has to be changed to E:

$$E = \frac{f^2 * (2\pi)^2 * L^3 M}{3I}$$

*Formula 2-12: Changed Formula 2-11 to E*

Now the values of the unknown variables have to be calculated. In case of the f, a test would yield the missing value. In this test, a carbon tube, which was intended for the copter frame, of 1 m length, an outer diameter of 18 mm and a thickness of 2 mm, was used.

The purpose of the test is to measure the Young's modulus of a carbon fibre tube. To start the test, the tube has to be fixed at one end to a rigid and heavy surface, like a

table. The free end has to be attached to a smart phone or something with the same functions. An accelerometer reading software should be installed on the device in order to perform the test. For this purpose, the android app “Accelerometer Monitor” was used.

When the recording of the application has started, a small impulse should be given to the end of the bar. If possible, the impulse should be initiated close to the phone. This initiates the movement. After a few seconds, the recording is stopped and the post-processing needs to be completed using a computer. If the curve of the accelerometer is loaded into the computer, it will count the cycles within a given time frame. In this case, there were 30.5 cycles in 5 seconds, giving a natural frequency ( $f$ ) of 6.1 Hz.

The results of the measurement are shown in figure 2-7 in a graphical presentation:

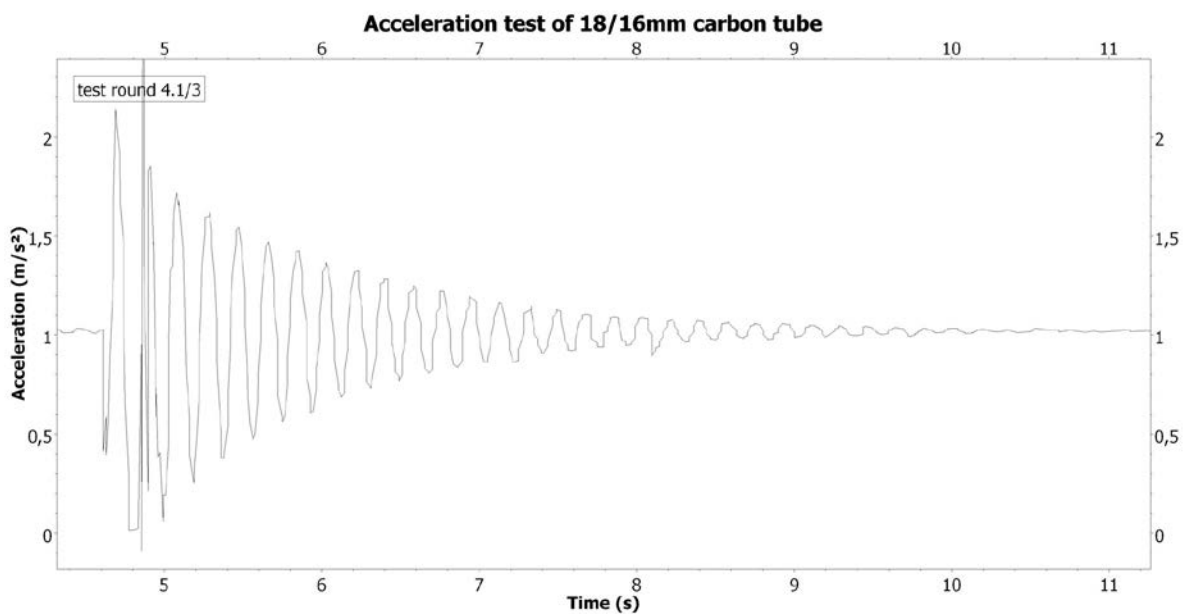


Figure 2-7: Acceleration test of 18 mm sqrt. CFRP tubes (own representation based on the software QtiPlot).

The remaining missing values were easier to calculate. The arm length was 1 m, the mass on the tip was 473 g. The value that was more difficult to calculate was the moment of inertia of the section. The value for  $I$ , taken from formula 2-11, is calculated using formula 2-13:

$$I_x = \frac{\pi((18 \text{ mm})^4 - (16 \text{ mm})^4)}{64} \approx 1,936 \text{ mm}^4$$

Formula 2-13: Calculation of  $I$

To calculate  $E$ , the calculated and the measured values have to be inserted into the formula, shown in formula 2-12. This results in the following equation:

$$E = \frac{6.1^2 \frac{1}{s^2} * (2\pi)^2 * 1000^3 \text{ mm}^3 * 0.473 \text{ kg} * 10^3}{3 * 1,936 \text{ mm}^4}$$

$$E = 1,196 * 10^5 \frac{N}{\text{mm}^2} \approx 1.2 * 10^5 \text{ MPa}$$

Formula 2-14: Calculation of  $E$

The calculated value was equal ( $E_{Literature} = 1.2 * 10^5 \text{ MPa}$  [54]) or at least nearly equal ( $E_{Literature} = 150 \text{ GPa}$  [55]) to different official sources for this material and was therefore very realistic.

Conversely, the propeller excitation has a frequency of 26 Hz, calculated from the product combination of propeller and motor, as shown in the table 2-1 (RPM/60):

Table 2-1: Data resource for Motor+Prop frequency calculation (own representation based on T-motor [42]).

Item No.	Volts (V)	Prop	Throt- tle	Amps (A)	Watts (W)	Thrust (N)	RPM	Effi- ciency (N/W)	Temp (°C)
U8 PRO KV170	22.2	T-MO-TOR 29*9.5CF	50%	6	133.2	19.3	1560	0.145	49
			65%	11.2	248.64	30.4	1900	0.122	
			75%	15.1	335.22	36.6	2080	0.109	
			85%	19.5	432.9	43.3	2300	0.100	
			100%	23.8	528.36	49.2	2460	0.093	
Notes: The test condition of temperature is motor surface temperature in 100 % throttle while the motor is running for 10 minutes.									

The result indicates that all calculations are correct and, more importantly, the vibrations do not influence each other as they are far enough apart (6.1 Hz to 26 Hz). With this knowledge it was possible to make a calculation for different tube lengths. The results are shown in table 2-2:

Table 2-2: Results of frequency calculation with different lengths

Length (mm)	Frequency (Hz)
1000	6.4
750	9.4
700	10.4
650	11.7
600	13.1

The calculated values ensure that, regardless of the real length of the tubes, all useful lengths will result an uncritical frequency. The most probable length should be 750 mm. This was due to the requirement of the size of the payload<sup>25</sup>. To avoid turbulences of the airstream, the propellers should be placed outside of the area of the mounting system. The propellers have a radius of around 375 mm. Together with half the size of the maximum payload (350 mm) a minimum size of 725 mm was required.

With the knowledge based on the frequency calculations, an operation of the motor/propeller and carbon tube combination would not be critical, at least with regard to the vibrations. A separate test would show if the stiffness would also be sufficient.

### *Centre Plate*

For a safe and robust construction of the copter, the core for the stability, the centre plate, had to be changed. As mentioned before, the small test plate was used to test the parts and the platform itself. For a productive operation the centre plate had to be replaced. Therefore a centre plate in the form of an X and with dimensions of 380 mm x 380 mm was designed. The preferred material was GRP given that CF plates would be much more expensive at a low increase of stability and a slight decrease in mass.

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<sup>25</sup> The required maximum size of the payload was 700 mm x 700 mm x 300 mm (WxHxD). For more details, see chapter 2.2.



Sandwich materials were not taken into account on the basis of their poor availability and the relatively high costs. The thickness of the plate should be at least three to four mm in order to receive very high stability in combination with a mass as light as possible. To build the plates it was planned to mill the plates using a suitable milling machine. To make sure that it was not necessary to build new frame parts in case the tube diameter increased, the centre plate was designed with additional holes enabling it to hold larger parts as well. At the moment of planning, the maximum diameter of the tube was set to 25 mm. Based on the existing mounting part dimensions for the 18 mm tubes from the frame kit, the required dimensions were scaled to the maximum possible, i.e. 25 mm tubes. To further ensure that the arms were well fixed and stiffness was maximised, the centre plate was equipped with some additional tube holder for each arm with the result that every arm would be held by a two point fixation.

Should the stability of the centre plate still not be sufficient, a vertical double-bow could be built, reaching from one arm over the centre plate to each single opposite arm. For some extra stability the bows should be in the shape of an X and stuck together. The material Curv could also be suitable for this task.

The designed centre plate along with the double bow construction is shown in figure 2-8. For a drawing derivation of the centre plate see annex IV and annex V. For the double bow construction see annex VI.

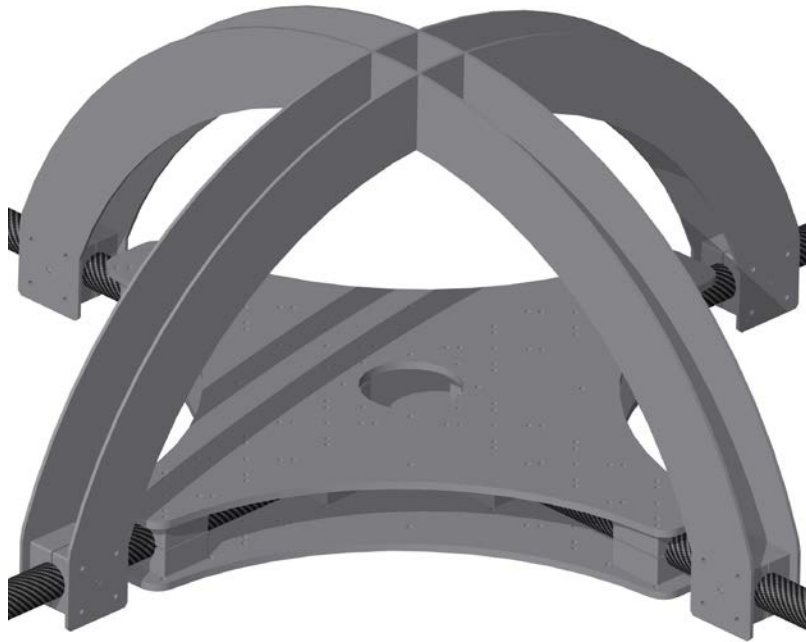


Figure 2-8: Centre plate with double bow construction (own representation)

### *Landing Gear*

Just as the vibration calculation for the frame was important, the same applies for the landing gear that should also avoid the occurrence of strong frequencies. For this reason, the use of a landing gear without “T” shapes was not an option. Therefore, a simple landing gear made of four legs with 500 mm x 18 mm CFRP tubes and a bumper on each end was developed. This had the advantage of very low costs and the possibility of an easy replacement in case a leg would break. The legs should be attached to the copter arms through an adapter plate. This landing gear that is easy to use also allows adapting the leg lengths of the copter. In favour of the light mass and the lowest costs possible the option of using a retractable landing gear was not considered. For the adapter plates the material Curv<sup>26</sup> should be used. This material has a very light mass and is made of woven synthetic fibre [56]. On this account, Curv was perfectly suitable for the requirements which were imposed on the material. The designed frame together with the landing gear is shown in figure 2-9. The drawing derivations are shown in annex VII and annex VIII.

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<sup>26</sup> Curv is the registered trademark of the company Propex Operating Company, LLC and describes a self-reinforced polypropylene composite [56].



*Figure 2-9: Design drawing of the copter frame including landing gear (own representation)*

### 2.1.9. Housing

To make sure, that the copter works equally well in rainy, snowy, very cold or very hot conditions, a protective housing for each sensitive (electrical) component had to be developed. The most sensitive parts are located in the area of the centre plate. Therefore, a solid housing for the centre plate should be designed. To ensure that the high capacity and high voltage LiPos are well protected, a waterproof box was planned. The box should have a silicone joint on its cover and should be placed directly under the centre plate. The (power) cords should be led out through a hole on the side and point towards the centre plate.

#### *Centre plate enclosure*

The centre plate itself received a separate housing. It was planned to print a perfectly fitting case, which enclosed the whole centre plate. This housing was composed of two parts that needed to be screwed together. On the edges, where both housing parts

should be plugged together, it was planned to set another silicone joint. When everything was assembled, every sensitive component in the area of the centre plate should be well protected against common environmental influences.

The 3D printer available, which allowed the printing of the required dimensions, did not support ABS material. Therefore, the print was made using PLA.

The housing of the centre plate was designed with a wall strength of around 2 mm. The top of the housing had a calculated volume of approximately 236 cm<sup>3</sup>, which corresponds to a calculated mass of ≈307 g with the density of PLA<sup>27</sup>. The bottom of the housing had a calculated volume of ≈288 cm<sup>3</sup>, which would correspond to a mass of ≈374 g of PLA. In sum, both housing parts had a mass of at least 681 g. This is a high additional mass for an aircraft making it necessary to look for a waterproof housing that was lighter.

Another way to protect the centre plate from water could be a combination of a tailored neoprene coat, a waterproof zipper and cables tied to the corners of the arms of the copter. This option has to be evaluated during the construction phase. An exploded view of the whole centre plate including the enclosure is shown in figure 2-10. The drawing derivation of the centre plate enclosure is shown in annex IX and annex X.

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<sup>27</sup> The manufacturer of the PLA stated that it had a density of 1.21-1.43 kg/m<sup>3</sup> [92]. Due to the large inaccuracies of the given evidence the rounded mean value (1.3 kg/m<sup>3</sup>) of the given density range was used.



*Figure 2-10: Exploded view of centre plate, carbon tube fixing points and enclosure (own representation)*

### *Motor holder enclosure*

The second parts, which had to be protected separately, were the housings of the motor holder. It turned out that these parts also needed to be printed. The design of these parts was much more complicated due to numerous interdependent factors, the most important being that the case should not be of a bigger size than the motor itself. This was because the more obstacles there were in the way of the air stream from the rotors, the less efficient the motor would be. The housing of the motor holder should also be waterproof. If the electronic components could not be placed in the region of the centre plate, it could be possible that not only the power cords would need protection, but also that many electrical control cables, the ESCs or capacitors would have to be placed

in the holder of the motor housing. This will become clear during first tests. Due to only little space in the housing, the electronic components should be strictly structured. To ensure a level of structure high as possible, a separate holder for the ESC should be used for the inner of the housing. In addition to that, the smaller electronic components and the wires should be located next to the carbon pipe.

The little space could also result in a heat accumulation. Should it prove impossible to use the electronics under normal temperatures, a suitable heat exchanger should be developed. To be prepared for the case that the heat in the inner of the case got too high, a way to conduct the heat to the outside of the housing should be set up. This may be achieved by a copper stripe, which is attached to the overheated electronics. This stripe could have attached cooling fins next to the electronics. However, there is the risk that the fins will not be able to dissipate the heat, owing to the lack of air circulation. In this case, it would be more promising to attach the cooling fins to the outside of the housing. This would have another advantage, because now the air stream of the rotor would be able to cool the fins well.

It has to be considered that the housing does not only hold the electronics, it also makes sure that the motor is well fixed. To allow this, the wall thickness of the housing and the infill<sup>28</sup> of the enclosure should be of an adequate strength. On grounds of the bad predictability of 3D printed objects, especially when different materials like ABS<sup>29</sup> or PLA<sup>30</sup> are mixed together, it was decided to avoid inaccurate calculations and to test the correct thickness in the construction phase.

On top of that, the power cable from the motor needed to be inserted into the motor holder housing. This required a waterproof cable routing and a plug system for high currents, also waterproof. To ensure easy access to the ESC or other components which are located in the vicinity, the case should be easy to open, e.g. for pulling some wires.

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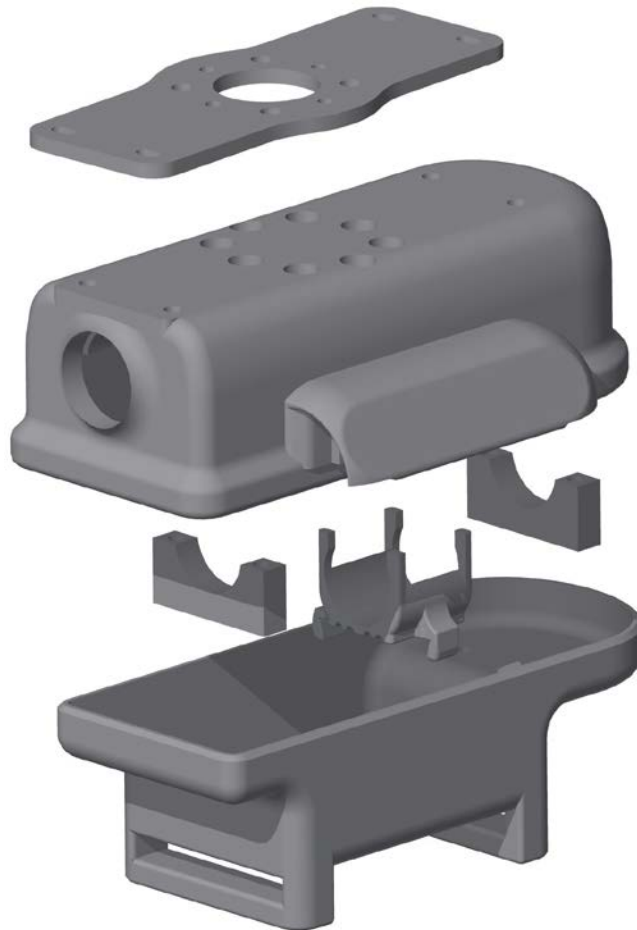
<sup>28</sup> Infill is a percentage value of the filling with filament inside of the printed object.

<sup>29</sup> ABS = Acrylonitrile butadiene styrene, a common thermoplastic polymer.

<sup>30</sup> PLA = Polylactic acid, a biodegradable thermoplastic aliphatic polyester.

The most important part, the motor, should be mounted on top of the housing. To ensure that the motor could be securely mounted, the motor should be attached to a very strong plate, like carbon- or glass-fibre. This adapter plate should be mounted to the housing of the motor holder. An integrated holding system which would be made from one piece would be desirable, but due to the expected instability of the printed parts a screwed solution with an additional adapter plate should provide the highest safety level.

To increase the understanding for the construction of the enclosure of the motor holder, the part was also drawn in the exploded view (figure 2-11). A drawing derivation for every used part of the motor holder and the motor holder enclosure is shown in annex XI to annex XVI.



*Figure 2-11: Exploded view of the enclosure of the motor holder (own representation)*

## 2.2. Universal Restraint System Development

The development of the restraint system was one of the key features of the research and development. The system is designed and constructed in the way that, when installed and used, it is able to hold goods with a maximum mass of 5 kg. Moreover, it should be able to take different types of goods. In the simplest case it would be sufficient to hold a square object. But it could also be necessary to hold a can or other bulky parts. In each case, it is important that the holding system is able to take almost all types of objects and allows their release at the right moment.

In order to reach this goal, different options had to be considered.

The first idea was to mount a combination of a belt and a ratchet system. This type of assembly would be an easy-to-use solution, which does not require a steady stream of electricity and would be of a very light mass. The payload would need mounting prior to the start of the UAV. To release the load exactly at the specified place, it was planned to open the belts using a rapid release coupling. The drawbacks of this approach are the risk of hanging belts getting entangled into the rotor. No assumption can be made about the possibility that this problem can be solved using a belt retraction system.

Another suggestion was to attach the freight using cords, which on one side would be mounted to a shaft and on the other side plugged into a rapid release coupling. To tighten the wires, a ratchet could be installed. The moment the freight shall be released, the rapid release coupling opens and the freight including the wires falls down. This approach has the advantage of a very light mass, a very easy structure and very low costs with a high potential of reproducibility at the same time. The disadvantages of this system are that it cannot be ruled out that the wires get entangled in the rotors. Furthermore, the system presupposes that the wires will be released too and it is likely that they will get lost on site. This would result in a high consumption of wires and fixing tools which in turn would lead to high costs in adaption over time.

A method of resolution that provides a mounting system that has been specially developed and constructed, only taking payload boxes of a specified design would not be considered. This was due to the missing universality of custom-built models. In the



case of a failure of the system, a spare part would not be replaceable promptly on grounds of the poor availability of the part.

Another option would be to mount one servo to each carbon pipe, which claws into the goods that need transporting. However, this solution was rejected for various reasons. The first was that the servo arm was not long enough to ensure a secure hold of the goods. The second reason was that it makes holding of different types of goods impossible. Finally, this solution was way too inflexible to be able to respond adequately to different sizes of the load.

### 2.2.1. Flexible Servo Arm

However, the idea above was further developed and resulted in the solution of an extended servo arm. These extended arms should be able to take larger objects with a maximum size of 70 cm x 30 cm x 70 cm (WxHxD). These dimensions are relatively large for the size of the copter. Therefore, it should be ensured that the bonding was sufficient to hold the items.

Prior to the design progress a suitable servo motor had to be chosen. A requirement for the servo was that it needed to be digital as the FC works better with this kind of servos. Moreover, a light mass (<25 g) and small dimensions were preferred. On top of that, the servo should cost not more than 35 EUR per piece and have a power output of at least 5 Ncm. Three possible servos were further taken into consideration.

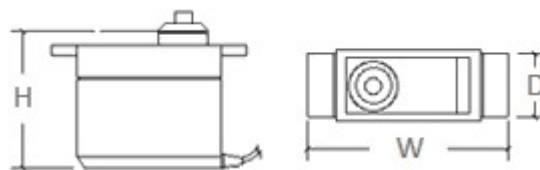


Figure 2-12: Conceptual presentation of a Servo with the letters for the dimensions (Own representation based on HOBBY KING TECHNOLOGY LTD. [57]).

The first was the Blue Bird BMS-390DMH. This was a high performance digital servo with a strength of 5.4 Ncm at 6 V, a mass of  $\approx 23$  g and dimensions of 40 mm x 30 mm x 13 mm (WxHxD) [58]. It has a pricing of  $\approx 20.00$  EUR incl. VAT. Figure 2-12 shows a schematic drawing of a servo motor with its dimension letters. It is representative for each of the described servos.

The second was the TURNIGY TGY-390V HV. It has a power of 5.4 Ncm at 7.2 V, a mass of  $\approx 23$  g and dimensions of 39 mm x 30 mm x 13 mm (WxHxD)<sup>31</sup>. The TGY-390V is  $\approx 22.00$  EUR incl. VAT per piece.

The third was the Goteck DA2311T. This servo has a power of 5.2 Ncm at 6 V, a mass of 23 g and dimensions of 42 mm x 30 mm x 10 mm (WxHxD) [59]. The Goteck is available at a price of about 19.00 EUR incl. VAT.

In comparison of these three servos it is remarkable that every servo almost has the same good properties. On paper, the Blue Bird is a little better, concerning the power and the power consumption. Due to the availability of the servos, it was decided to use the Bluebird, which would be the first choice in this comparison.

To make sure that the mounting system is easy reproducible, it was tried to use different acrylic plates (casted) with a thickness of three (two times) and four (three times) mm. In combination these particular strengths allowed the overall thickness of 18mm. In fact, the casted acrylic plates had a scattering, owing to the production conditions, of minus 20 % to plus 30 % of the thickness of the plates<sup>32</sup>. Thus, the maximum thickness could be more than 23 mm. The massive scattering makes it impossible to calculate a suitable holding mechanism. Therefore, it was decided to use the official scales for the constructional planning and adapt them when the real parts would arrive.

For an easy reproducibility it is possible to use other materials like compound materials, such as glass or carbon fibre plates or for a low-cost rebuild, particle or glued laminated board would be suitable as well. The used plates should be cut to convex formed arms. These arms should be screwed or glued together and mounted directly onto the servo. A little shovel with a ratchet mechanism is to be mounted at the end of the arm. The shovel itself should be mounted between the outer plates that are slightly shifted downwards. This shift also allowed it to narrow the thickness of the servo mounting.

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<sup>31</sup> Unfortunately, the servo is not manufactured any longer. Therefore, the data was collected from RCRreference.com [91].

<sup>32</sup> This information came from the company STYXIS in Berlin which was in collaboration with this project concerning the procurement of the acrylic plates.

The ratchet was needed to allow attaching the object easily to the copter with the servo controlled arms. To ensure that the ratchet was also easily reproducible, all parts for that were made of standard parts. To ensure a perfect fixing, the shovels need to point directly to the object. The ratchet mechanism allows it to hold the shovel in the desired position. In the conception drawing the size of the arm was 405 mm long, the shovel having a length of 155 mm. Screwed together, the overall length was 530 mm. For a reduction of mass, the arm was to be notched out. To connect the arms of the mounting system to the servo it was planned to change the servo arm. The chosen servo should be delivered with servo arms made of plastic but was to be replaced with an aluminium-made arm. To realise ultimate strength between the servo arm and the mounting arm it was planned to cut a groove into the mounting arm where the servo arm could be placed and fixed.

With the length of the arm of around 400 mm the servo has a force of 1.35N at the outer point. This is calculated as shown below:

$$F = \frac{M}{r} = \frac{0.54 \text{ Nm}}{0.4 \text{ m}} = 1.35 \text{ N}$$

*Formula 2-15: Force calculation for a 54Ncm servo at 400mm.*

A force of 1.35 N at around 400 mm is not much, but for lighter, bulky objects quite usable.

Figure 2-13 shows the developed flexible servo arm of the flexible mounting system. Every self-made part of the arm is shown in the annex. For the flexible servo arm see annex XVII to annex XXIII.



*Figure 2-13: Two views of the concept drawing of the flexible servo arm (own representation)*

The servo and the arm should be mounted to the carbon pipe of the copter. This was done through a 3d-printed servo holder. This part of the copter cannot easily be rebuilt without a 3d-printer, but on the basis of the servo holder construction, there is no other suitable way to mount the servo easily to the copter.

### 2.2.2. Fixed Servo Arm

To ensure the ability of transporting objects with a higher mass, a second version needed to be developed. A flexible mounting mechanism should not be implemented. The use of a fixed arm made from one part would result in a mass reduction of the entire gripping system due to the missing mechanics. This mass reduction could be used to install more powerful servos with a higher mass.

The servo should have a torque of at least 30 Ncm and a mass of not more than 60 g. The pricing should be below 60.00 EUR incl. VAT.

A possible servo for the solid arm was the Blue Bird BMS-2514 7.4 High Voltage / Coreless Digital Servo. This servo has, other than the servos for the flexible arm, a great excess of power. At 7.4 V the servo has a power of 33.2 Ncm. This is much more than

the class of servos used for the other design of the arm. This benefit comes with the price of a higher mass and a greater size. In numbers this means that they have a mass of 58 g per piece and dimensions of 55 mm x 39 mm x 20 mm (WxHxD) [60]. In the relation to their output, the mass and dimension of the servos were relatively small. The BMS-2514 is available for around 58.00 EUR incl. VAT.

The second option of a high voltage servo was the HobbyKing HK47903TM. This servo provides a max. Torque of 31 Ncm at 7.4 V [61]. It has a mass of around 58 g, which is the same like the Bluebird. The size of the servo is also approximately the same [55 mm x 38 mm x 20 mm (WxHxD)]. It costs about 41.00 EUR incl. VAT for each piece. That is nearly one third less than the Blue Bird.

Unfortunately, it was not possible to find a third servo which has matching properties for the formulated restrictions. Therefore, the comparison is between the two servos, discussed above.

Given that both servos almost have the same characteristics, the only difference being in the price, the choice was made in favour of the HobbyKing servo.

The solid arm of the mounting mechanism was developed with the aim of providing a simple way to attach items below the copter. It should not be necessary to screw or glue anything. Similar to the flexible arm, the arm should be notched out in order to reduce the mass. Following the concept, the solid arm has an overall length of 41 mm. The fixing point is at around 350 mm length. The thickness of the mounting arm made from one part should be 12 mm. This was the maximum size available and that suitable cutting systems were able to cut<sup>33</sup>. The applicable materials for the fixed arm construction were almost the same as used in the construction of the flexible mounting arm. At this point it will therefore not be mentioned a second time.

As shown above, the arm has a force of around 8.9 N at the point 350 mm away from the servo sprocket. This was calculated as follows:

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<sup>33</sup> This was described in more detail in the construction part.

$$F = \frac{M}{r} = \frac{3.1 \text{ Nm}}{0.35 \text{ m}} \approx 8.9 \text{ N}$$

*Formula 2-16: Force calculation for a 31Ncm servo at 350mm.*

This power allows it to take high mass parcels with a maximum mass.

Following the aim of simplicity, the servo and the constructed arm should receive a locking mechanism of the simplest way possible, especially with regard to an easy reproduction. Therefore, the servo should not be mounted in one 3D printed part, but rather in two simple plates, with the servo. For this construction a GRP-Plate with a thickness of two to four mm could be used, but for reproduction a particle- or wooden board, which is tailored and drilled adequately could also be suitable. A conceptual drawing of the constructed fixed servo arm is shown in figure 2-14. For the self-made parts of the fixed servo arm see annex XXIV to annex XXVI.



*Figure 2-14: Design drawing of the fixed servo arm (own representation)*

At this point, the *BEAST* was theoretically ready to take off; it just had to be built. A design drawing of the UAV is shown in figure 2-15. The drawing derivation of the whole copter is shown in annex XXVII.



Figure 2-15: Design drawing of the whole UAV (own representation)

### 2.3. Electrical Design

After the copter and the universal mounting system had been developed, the electrical design could be drawn. As a result, figure 2-16 was generated:

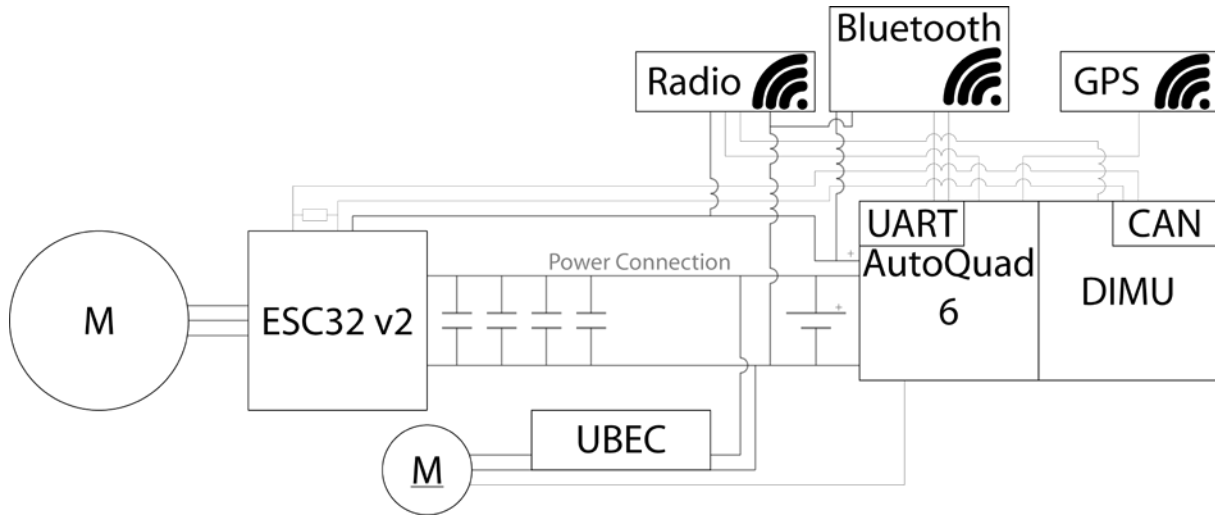


Figure 2-16: Planning of the electric circuit of the copter (own representation)

The thick grey wires in the circuit represent power cords. The thin, black wires stand for data wires. The main components of the circuit comprise the power supply, the AutoQuad FC and the AutoQuad ESC32. The DIMU board was an add-on module which was plugged directly onto the AQ6 board allowing it to extend the ports and the functionality of the AQ6 FC. The DIMU provides a CAN distribution with integrated terminator. The CAN bus was used to transfer the control and telemetry data and was plugged into the ESC. A  $120\ \Omega$  resistor should be placed between the CAN-L and the CAN-H line [62]. Owing to the separation of the logic unit and the motor power distribution inside of the ESC, the ESC needed a second power wire which provided 5 V [37]. Fortunately, the AQ6 Board provides a 5 V power output of up to 1 A [63]. At the output of the ESC there are three-phase current wires that were used for the power supply of the motor (M).

The AQ6 and DIMU board also allowed the plugging of the radio and the GPS antenna. The Bluetooth module was also attached to the AQ6 board. This configuration allowed a parallel usage of Bluetooth and the transfer of telemetry data to the radio.

To realise the control of the universal mounting system the servo motors needed to be controlled. This was done through a PWM port of the AQ6. To power the servos, the



use of a UBEC, which transformed the voltage of the LiPo from around 22.2 V to different voltage ranges, was planned. This was due to the fact that the voltage range would be relatively low at the point when the servo motors (M) provided most of the strength. As a result, the 22.2 V of the LiPo would destroy the electronic of the servo immediately.

The circuit was drawn exemplarily for one motor and one servo. The whole system consists of four of them for each part.

## 2.4. Software

In connection with this paper many different types of software were used. The calibration was done with the QGroundControl for different platforms. Because of the beta status of the ESC32v3 it was not possible to do a calibration using the QGC. It was therefore necessary to do the test and the calibration via the serial interface program and a programme especially written for the calibration. The revision 3 of the ESCs needs to be configured and tested using a terminal programme for the communication via a serial port—for e.g. PuTTY [64]—and the application `esc32cal`<sup>34</sup> [65]. Both will no longer be required, when the ESC has officially been released. The manufacturer of the AutoQuad electronics announced that upon the release of the ESC the QGC would also be updated. Therefore, the description of the software focused on the QGC.

### 2.4.1. QGroundControl

The most important software which was used was the QGroundControl<sup>35</sup>. This software was available for Windows, Linux and MacOS and was used to configure the AutoQuad FC and the AutoQuad ESC32 ESCs for the revision 2. This software also enabled it to receive live telemetry data from the electronics.

The QGC was primarily used to configure the AQ FC and the AQ ESCs. The user interface of the software is depicted in annex XXVIII. The latter proved to be most complex. This was due to the fact that electronics did not work well, making a manual configuration of the ESC32 necessary in version 2. As previously written, the ESC32 in the version two does not work well, the alternatively chosen ESCs, the T-Motor air40, also did not perform well, but for them there was no need of a software calibration. In the final version, the used ESC32 was in the version three which allowed the partly automatic calibration of the right motor parameter.

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<sup>34</sup> The programme `esc32cal` was available for Windows and Linux.

<sup>35</sup> “QGroundControl is a community effort to build a next generation micro air vehicle ground control station. The base code was developed 2009-2010 in the PIXHAWK Project at ETH Zurich by Lorenz Meier. It is since 2010 under community development with a wide range of projects and individuals.” [93]

To get live access to the ESC32, the ESCs were plugged onto a regular computer with a universal asynchronous receiver transmitter (UART) [66]. Not only did this allow configuring the ESC with the QGC, it also enabled the use of the software PuTTY. This software established communication with the ESC Command Line Interface (CLI), using a serial terminal. The COM port that the ESC32 was connected to was set to a baud rate of 230,400 bps [67]. Among many other functions, this application allowed seeing the live current during the performance of tests or during operation. This permitted a very precise estimation of the suitable calibration values.

The configuration of the FC was not particularly demanding. First of all, the AutoQuad M4<sup>36</sup> board had to be flashed with the required firmware. The firmware should be prepared for the AQ M4 v2 (r6) board with external ESCs, a HoTT telemetry or Bluetooth output and—for the time being—without a Quatos<sup>37</sup> licence. After the firmware was chosen and downloaded the AQ M4 board was connected to the computer through the UART. In the mission section of the QGC the sub item for the firmware update needed to be selected and the required COM port and baud rate was entered. A few seconds after the button “Flash Firmware” had been pushed, a reboot of the board was necessary. Now the serial connection had to be established. Following that, the values for the type of radio and the associated channels could be set. Finally, the type of voltage measurement was set to 1 (external voltage sensor).

In order to achieve the best results, the ESCs should at least have the parameters shown in table 2-3:

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<sup>36</sup> The reason why the AutoQuad M4 board was used and not the AutoQuad 6 board was described in chapter 9.1.2.

<sup>37</sup> Quatos is a nonlinear adaptive attitude controller add-on for Autoquad. It can be used to replace the default PID controller with a more robust and responsive attitude control in the presence of increased turbulence and wind gusts. It also adapts to off centric mass and motor imperfections without retuning. The Quatos add-on is not open source. It is developed, maintained and supported by Drone Controls [99]. A license is priced in two parts. Hobby crafts up to 2.5 kg are priced at 99 \$ and a commercial Quatos license for crafts weighing up to 10 kg are priced at 995 \$ [100]. Due to the very expensive price of the required license it was renounced from procuring one.

Table 2-3: Description of important ESC parameter for a high-quality calibration [68]

Parameter name	Parameter description
• <b>ADVANCE</b>	The amount of timing advance in electrical degrees. There are 60 electrical degrees in a commutation cycle. This value can be set from 0 to 30 degrees.
• <b>START_CURRENT</b>	The amount of current in amps presented to the motor during startup.
• <b>MAX_CURRENT</b>	The maximum amount of current in amps that the ESC will allow. Current is dynamically regulated.
• <b>START_VOLTAGE</b>	The amount of voltage presented to the motor during startup. Allowable range is 0.1v to 3.0v
• <b>SWITCH_FREQ</b>	The output PWM pulse frequency used to power the motor windings in KHz. Valid range is from 4KHz to 64KHz.
• <b>MOTOR_POLES</b>	The number of magnetic poles used in the motor's construction. This value only needs to be set correctly if it was planned to use the RPM closed loop mode.
• <b>DIRECTION</b>	The direction of the rotation of the motor. This value can be set to forward or backward.
• <b>GOOD_DETECTS_START</b>	Once started, the number of good, in order zero crossings needed to be detected before the motor is considered to be in the running state.
• <b>BAD_DETECTS_DISARM</b>	The number of missed zero crossing detects allowed before the ESC considers the motor not to be running at which point it will go into the disarmed state.
• <b>PWM_RPM_SCALE</b>	The scale of the input PWM pulse length. In closed loop RPM run mode, PWM_LO_VALUE will indicate 0 RPM and PWM_HI_VALUE will indicate this RPM. Closed loop modes only!

<ul style="list-style-type: none"><li>• <b>FF1TERM</b></li></ul>	Feed forward terms used for the RPM controller. Closed loop RPM mode will not function until FF1 & FF2 terms have been set
<ul style="list-style-type: none"><li>• <b>FF2TERM</b></li></ul>	These values should be calculated using the esc32Cal program with the -r2v option

In addition to the ESC calibration the manufacturer was asked for some specific parameters for the motor. However, this technical data sheet of the motor did not provide every required value [42].

One missing value that was of most importance concerned the amount of poles the motor has. Normally, the number of poles could be determined through counting, but owing to the waterproof enclosure of the motor this was not possible (see figure 2-17). After a long period of inquiries and replies the manufacturer gave the answer to the ultimate question of live, the universe and everything: 42.



*Figure 2-17: Diagonal bottom side of the closed motor (own representation).*

A member of the AutoQuad development team had tested and configured almost the same motor and ESC configuration.

The most important values for the configuration can be seen below:

- GOOD\_DETECTS\_START = 48
- START\_VOLTAGE = 1.5
- START\_CURRENT = 0.5
- MOTOR\_POLES= 42
- MAX\_CURRENT = 20.0

Based on this knowledge, the ESCs could be configured. The protocol of the configuration is shown in Annex XXX. The result of the calibration is shown in figure 2-18 and 2-19:

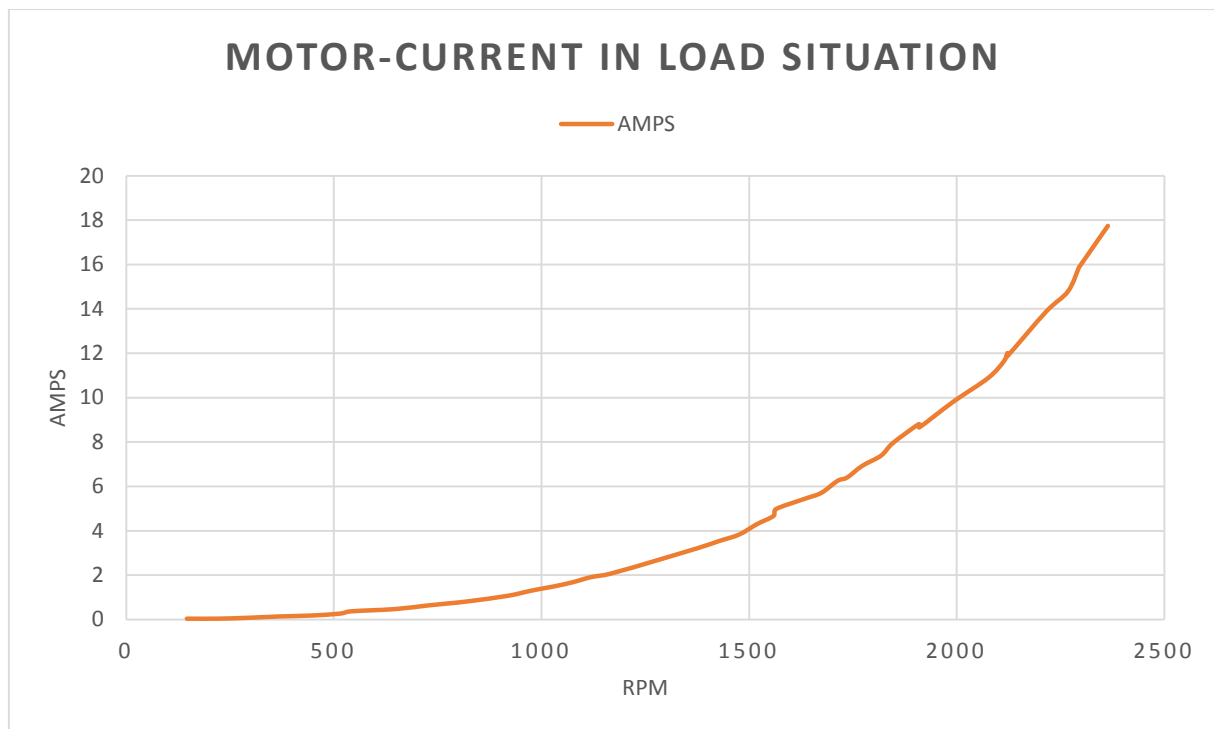


Figure 2-18: Performance data during ESC-Motor calibration (AMPs to RPM) (own representation)

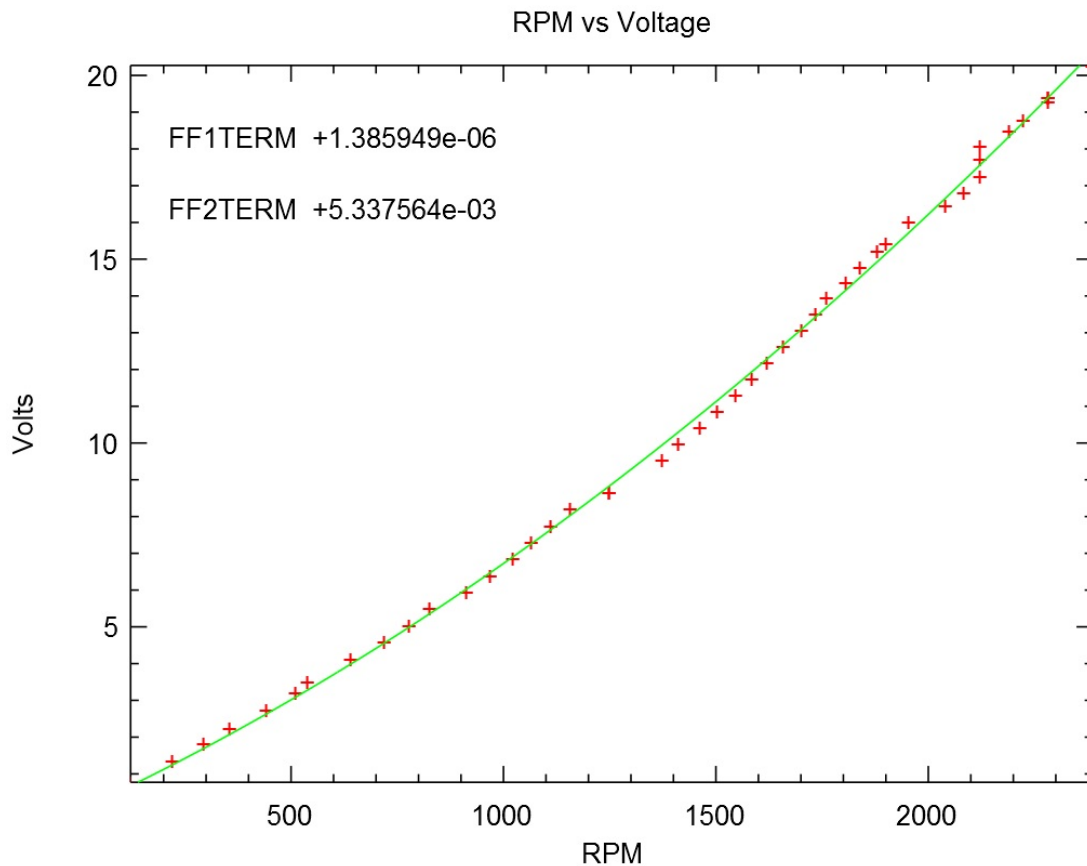


Figure 2-19: Performance data during ESC-Motor calibration (Volts to RPM) (own representation)

After the calibration was done the last missing values were calculated:

- FF1TERM +1.385949e-06
- FF2TERM +5.337564e-03

The value PWM\_RPM\_SCALE could be derived from the details of the calibration (see annex XXIX). There it is the last RPM value which is interesting. In this case it is 2364 RPM. In order to set the PWM\_RPM\_SCALE to the value suitable for the motor it should be set to 2350 RPM<sup>38</sup>.

Other missing values for the configuration – ADVANCE, SWITCH\_FREQ, DIRECTION and BAD\_DETECTS\_DISARM – were set to default. If necessary, they could be set later on. The used parameters of this configuration are shown in annex XXX.

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<sup>38</sup> The value should be set slightly below the measured value.

After every essential function was configured the copter itself was ready to make some test flights and to check the function of the universal mounting system.

#### 2.4.2. QGC for Android

To control the copter much easier and in order to receive live data a special enhancement of the QGC could be used. This allowed using the QGC with android. The development of this software was based on the copter control gcs by Bart and it was tailored for the use with AutoQuad for some enhancements [69]. This software in combination with a Bluetooth module attached to the AutoQuad board allowed using a smartphone or a tablet with an android operation system (OS). The advantages of controlling the copter with a mobile device lie in the easiness and also the probability that most of the people that would need to control the copter should have at least a smartphone or a tablet. With this minimal configuration it would be possible to set start and landing points, mark waypoints and enter special actions, such as the airdrop of the payload. On the other hand, a Bluetooth connection does not have a very wide range. Therefore, it should be ensured that the commands, entered into the QGC for Android, would be clear, because when the copter starts the flight and goes out of range, there is no chance of stopping him.

The tools were very easy to install and useable for every android-based mobile device with Android 4.x and later [70].

The used version of AutoQuad Android GCS was in the version 0.3.5 and supported the following features [70]:

- HUD (Head Up Display) with battery voltage, altitude, GPS info
- PID settings – display and configure
- Access to all parameters
- GPS location of AutoQuad
- Full screen mission planner with waypoint editor
- Text-to-speech – all AutoQuad messages can be spoken
- Radio output screen (diagnostics)



To connect any of the named and suitable mobile devices to Bluetooth the application has to be started and thereupon scans for a Bluetooth adapter in range, connecting to the Bluetooth adapter attached to the AQ board.

In the main view of the application a HUD is displayed on the left side and the current GPS position on the right side. To start the mission planning, the view has to be changed to the planning view, where it is easily possible to tap a waypoint and place it onto the map screen. Following this, the type of waypoint has to be set.

The possible waypoints were [70]:

- Waypoint
- Take Off
- Orbit
- Landing
- Return to Launch

After the planning was done the mission had to be saved and transmitted to the AutoQuad FC.

To demonstrate the easy and remarkable functionality a test flight was planned using the android application. The test flight included a take-off, several waypoints, two orbits (cycling around a waypoint for a defined amount of time), a return to launch (RTL), and a landing. To set the points it was necessary to tap on the desired point on the map. After that the type of action should be chosen. If required, specific parameters, such as flight speed, altitude or exact GPS coordinates could be set for every single waypoint. The described plan of a test flight is shown in figure 2-20.

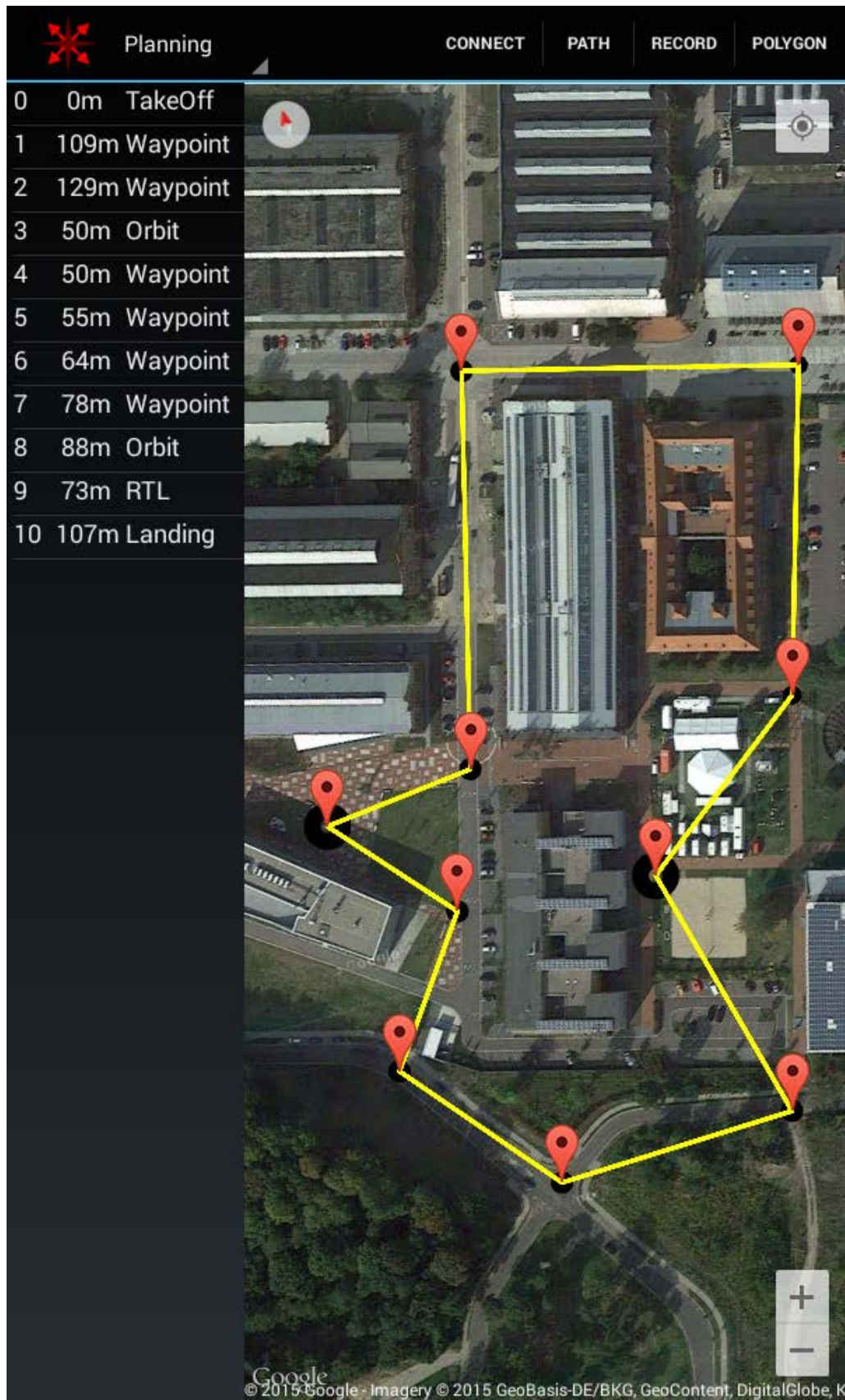


Figure 2-20: Screenshot of Flight Planning with QGC for Android around the TH Wildau campus (own representation)

In the case of an incorrect waypoint it was possible to edit a waypoint afterwards. On top of that, every proportional, integral, and derivative controller (PID) related value could be tuned in the PID editor.

### 3. Construction

As already mentioned, for the beginning of the building phase a testing centre plate with pre-soldered contacts and an integrated power distribution board could be a base for experimental testing of the electronics.

A supplier of the AutoQuad electronics also provides suitable copter starter kits, which have the characteristics as described. Therefore, a starter kit was ordered, which contained a pair of centre plates, clamps, screws and further equipment that was needed to build a copter in an easy way. From the outset it was clear that, due to the size and the thickness of the board, this could only be a transitional solution.

### 3.1. Construction of electronic components

First of all, attempts were made to place the chosen components around the centre plate. Therefore, the ESCs, the capacitors, and the whole power distribution were soldered to the board. After that, the electronics were attached on top of the centre plate. Lastly, every component had to be connected to each other. For this basic version some calculations could already be made. The AutoQuad FC allows the calibration of the installed measuring units.

#### 3.1.1. Calibration

One of the most important reasons the AQ offers the best flight results, is its ability to estimate its altitude, velocity and position in 3d space using the on-board inertial measurement unit (IMU) along with GPS and air pressure sensors [71]. To estimate the velocity and altitudes precisely, the Gyros, the accelerometers and the magnetometers should be calibrated. This should be done in order to compensate manufacturing differences and temperature-induced drifts of the sensors. There are different versions of the AutoQuad board available. Some of them use analog sensors; others use digital sensors, which are attached through a pluggable daughter board. Depending on the type of sensors the AutoQuad board uses—Analog IMU (AIMU) or Digital IMU (DIMU)—there are different methods of calibrating the sensors [71]. The purpose of the process is to gather sensor data and using it to calculate sensor offsets and ranges and align the sensor axis to each other.

The purchased AutoQuad board has a pre-soldered daughter board on top. Therefore, both variations are available, the AIMU, which is on-board the AutoQuad board, and the DIMU, which is attached through the daughter board.

For the newer DIMU-based boards there is the option to use a simple on-board “level” calibration and a compass calibration. The ability to fly is on a basic level, which is quite useful but improvable, therefore a manual calibration would be the best way in any case. Beyond that, there are dynamic and temperature compensated calibrations, which should be done in further refined IMU calibrations. A calibration of the older AutoQuad V6 AIMU boards would be more difficult, therefore the manufacturer suggests upgrading a V6 board with a DIMU [71].

The digital sensors also achieve a high degree of precision. In detail, the pressure sensor should work very accurately and the compass would be much less susceptible to magnetic distortion from the power distribution. This is due to the DIMU; the compass is only used to estimate initial heading before take-off. If the copter is armed<sup>39</sup> and a flight is done, the compass would no longer be contributing to heading estimation and therefore not be susceptible to heading distortion caused by magnetic fields in flight. On top of that, it is possible to write into the EEPROM of the board to store IMU parameters [71].

This could be very helpful to avoid a loss of the calculated IMU parameters, e.g. while an update occurs.

Many copters available on the market come with a self-calibrating option. So why is it advisable to do the calibration? This is because every sensor is different, even from the same batch. Ranges, bias and alignment varies from sensor to sensor, and if they are not compensated individually the copters might not fly or the estimation filters would have to work harder to keep it flying [71]. The better the data the controller was fed, the better it will be able to estimate the altitude, heading, speed and position of the craft.

#### *Static Flight Control Calibration*

The calibration was done in a number of steps. The first was the static calibration. For the static calibration a full temperature compensation had to be conducted. If this calibration procedure was done correctly, it should be possible to earn a very accurate calibrated IUM with full bias, scale and alignment compensation which normally has the characteristic of a very little drift over a large temperature range [72]. The requirement of a static data calculation is to record data about how the sensor values change with the change of the temperature. In very simple terms it is the freezing of the board and letting it thaw slowly under its own heat while kept absolutely still (static) and

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<sup>39</sup> To arm a copter, respectively a FC, means to make the copter ready to fly. This enables the possibility to start the motors.

logging the changes in the individual sensors. This data is then used to calculate calibration values for a particular board. To proceed with the calculation an airtight and insulated container had to be built; so small that it could just hold the AutoQuad board. For this step a small plastic food container filled with foam was used (other dry insulation material could also be used).

Once the box was prepared, the AutoQuad board had to be placed in the box and in consequence the box had to be put into the freezer at a temperature of at least  $-15^{\circ}\text{C}$ . The used freezer reached  $-25^{\circ}\text{C}$ , which was more than sufficient for the requirements. While the board is in freezing process the cover of the box should just lay loose on top of it. The freezing at not less than  $-15^{\circ}\text{C}$  needs at least one hour. To be on the safe side, the freezing process was extended to two hours. After the freezing was completed, the box was closed directly in the freezer. Then the box had to be placed in an undisturbed area with no running appliances, electrical devices or A/C power lines nearby, such as a fireplace or something equal. When the box was placed in a suitable area the board had to be powered. This way the board would slowly heat the compartment through the emitted heat of the board itself. The unfreezing could need up to 90 minutes. After the time elapsed, the power supply should be disconnected. The manufacturer recommended doing this three times, each time pointing in different directions in order to expose the acceleration sensors and magnetometer to different angles of the earth's gravity and magnetic fields<sup>40</sup>.

After the freezing and unfreezing process was done three times, the recorded data should be analysed in the AutoQuad custom version of the software Qgroundcontrol station<sup>41</sup> (QGC) [73]. When the files were loaded into the QGC the first thing which had to be checked was the temperature. In the attribute LOC\_ADC\_TEMP0, from the

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<sup>40</sup> First the board was oriented with a corner pointing to the earth, in the second freezing session the board was oriented with the opposite of the first corner to the earth and during the third session the board was oriented to the board level.

<sup>41</sup> This software was written under the GPLv3 licence and was based on the PIXHAWK's Ground station. The software was enhanced by a joint effort with the community [93].

parameter list, the value for the temperature can be found. The delta of the temperature should be of about  $-20^{\circ}\text{C}$  and  $48^{\circ}\text{C}$  on an average of 90 minutes. In the case of high spikes or drops in the shown curve, the sensor could probably have a condensation glitch. In this case the freezing should be repeated. However, the data from the freezing was promising, also concerning the other relevant recording sections. Therefore, the freezing process and with it the most complex element of the static calibration was completed.

#### *Dynamic Flight Control Calibration*

The next step was the dynamic calibration. This stage concerned the aim to gather, scale and offset data for gyroscopes, accelerators and magnetometers [74]. This was done by a series of coordinated moves, also known as the calibration dance. To receive an AIMU compass which would compensate all soft and hard iron magnetic effects in the frame, the dynamic calibration had to be performed with the AIMU board installed in the powered airframe in a complete flight-ready condition, leaving aside the propellers which are not magnetic. For the version with the DIMU installed, the compass compensation should be performed in the same way as the AIMU was calibrated.

The dynamic calibration consisted of a special sequence of rotations. It would be considered, that the frame of the craft has six sides, like a cube:

- Top face
- Bottom face
- Right face
- Left face
- Front face
- Rear (back) face

To start the calibration, the face has to point up. Then the craft has to be rotated 90 degrees to an adjacent face and back up. After that, this rotation has to be repeated until all four adjacent faces have been covered (front, back, left right). Then the copter has to be rotated slowly in order to bring a new face up. Then the last four rotations to the adjacent faces have to be repeated. During this procedure, the copter should be



slowly rotated on its own axis. The best way to do this was to rotate the body of the person, who performed the dynamic calibration.

After all the data was recorded, it was necessary to calculate the calibration values for the copter. This step was more complex and took up some time. This was mainly due to the many individual steps the software needed to run through. After the calculation was processed by a computer, the generated parameter file was uploaded to the QGC and from the QGC to the AutoQuad board. Once this was done, the static and dynamic calibration of the board was completed.

### *ESC Calibration*

The next step was to calibrate the ESCs. As already described in the copter development part, the AutoQuad ESC32 was used. This well performing ESC should be the best choice for the combination with a AutoQuad FC. Along with the chosen motors, which should work well with 5S<sup>42</sup> the calculation was expected to be very easy and quick to perform. Unfortunately, that was not the case. This was due to the fact, that the motor did not work well with 5S.

The first tests with this ESC did not turn out to be very successful. In a calibration test, the ESCs were running for 5 min. and reached a temperature of 70° C. At this point the test was aborted.

#### *3.1.2. Re-Planning of Electronic Components*

To avoid most of the interfering sources that were likely to occur, the structure of the copter was slightly changed. For the next tests it was planned to put the ESCs right next to the motor. This was due to the fact that the longer the three phase power cords would be, the more interfering signals that could influence other electronically components, like the FC, could be emitted. To avoid damage to the ESCs through high voltage peaks, low ESR supporting capacitors were applied. This experimental setup required placing every component that needed to be near the ESC in the housing of the motor holder. As a result, the control wires also needed routing through the carbon

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<sup>42</sup> which was confirmed by the manufacturer after a request

tube to the ESC. To avoid manipulations of the signals which would be sent through the wires, every set of cables that belonged together, was twisted together.

During the tests the motor had a temperature of 80° C which was way too high. This result suggested a poor calibration and a very high timing resulting in frictional heat. To avoid further over temperatures, the tests were aborted at this point. After many hours of testing it was decided to upgrade the UAV from 5S (18.5 V) to 6S (22.2 V). This step required to change the voltage transformer (RECOM) on the FC. This was, apart from some soldering work, an easy step. Unfortunately, the ESCs could not be upgraded that easily. Therefore, the use of a different ESC was considered. A market research and a second inquiry at the manufacturer's highlighted the T-Motor Air40 ESC. They should perform with the T-Motor U8 Pro KV170 in the best possible way.

When the new ESCs had been obtained the motor tests started immediately with satisfactory results. The first test was performed using a servo tester. For an advanced test, the ESC was connected to the FC. Unfortunately, this combination worked even worse than the ESC/Motor combination which had been used before. At this point the tests were stopped once again, the reason being that the AutoQuad announced the release of the next generation AutoQuad ESC32 (v3).

This new ESC would provide much more features, an auto calibration and, most importantly, the support of at least 8S LiPos and an output of 500 W with peaks of up to 700 W allowing the continuous operation with normal cooling [75]. The manufacturer assured that the ESCs had been tested under experimental conditions for up to 10 or 12S and more than 1kW. But this would only be possible in optimal conditions with special settings, cooling and airflow over the ESC. Therefore, the previously planned development could be resumed again and the subjective best flight results could be achieved. The question now was simply, would the ESCs arrive in time?

Unfortunately, the AutoQuad ESC32 in the revision 3 was not released during the writing of this thesis. However, to support this project the manufacturer provided a few beta platines of the new ESC32 v3. It proved very useful that the new version of the ESC had the same dimensions like the previous version ESC32v2. Therefore it could be placed into or be attached to the built parts of the old version of the ESC.

Fortunately, before the latest ESCs could be tested, a large difference between the v2 and v3 ESCs would become clear. The ESCs provided the ability to be controlled with a PWM and a ring bus technology. While the ESCs in version 2 could be controlled using both technologies at the same time, the ESCs in the version 3 could only be controlled by one or the other.

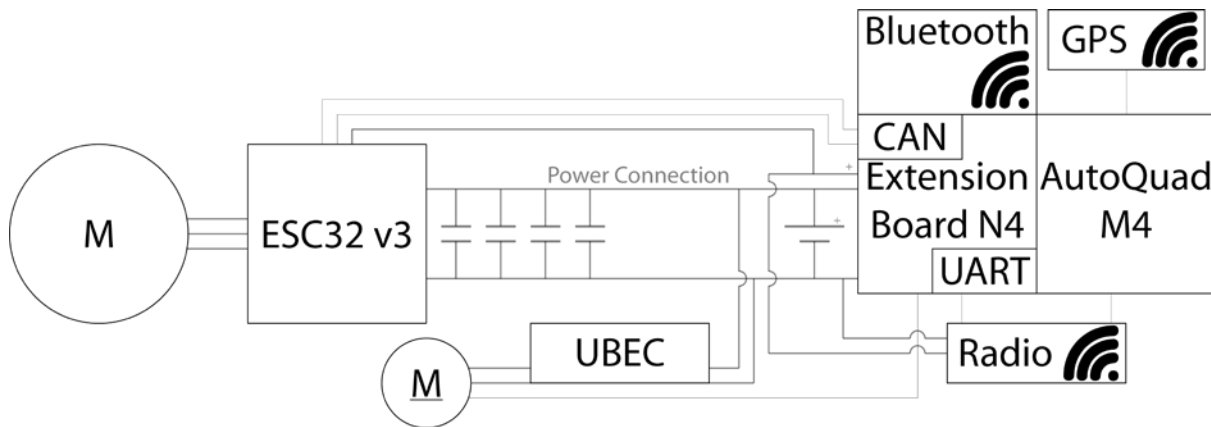
Given that the ESC just needed a calibration which was done using different software tools, the description of the calibration was moved to the chapter on the software.

During the conduct of some of the tests a flash occurred due to the residual voltage of the capacitors. Unfortunately, this resulted in a damage of the microcontroller (MCU) on the FC. The manufacturer tried to repair the FC and change the MCU but this did not work. For this reason, the AutoQuad 6 FC and the DIMU had to be replaced. Matters were complicated further when the AQ distributor ran out of stock of the boards. The only alternative was to take another board and then try to use this one. The AutoQuad M4 board was released at the end of 2014 and provided every function which was required [76]. Along with the N4 extension board each required port was accessible.

The advantage the new boards was that the freezing and the complex calibration procedures were no longer necessary [77]. The required calibration process was done within ten minutes owing to the fact that it was now possible to start an accelerometer calibration with the sticks of the radio control [78]. This calibration took around 5 seconds. The second and last calibration was the magnetic calibration. To perform this calibration the copter with all parts attached had to be rotated into every possible position. This calibration took around five minutes. After that the calibrated data had to be saved to the EEPROM of the copter and at this point the copter was able to start and also perform with very good properties.

### 3.1.3. Updated Electrical Design

After the redesign was completed, the electrical design of the copter had the following structure:



The circuit was drawn exemplary for on motor and one servo. The whole system has four of them for each part.

### 3.2. Building of the Centre Plate

As described before, the test centre plate was used to do some tests. Since all possible tests were done up to this point, it was necessary to change the centre plate. For the new centre plate a 4 mm CFRP plate was used. This plate was strong enough to hold everything that it was intended for.

To bring the plate into the desired form, a milling machine was used. At the Technical University of Applied Sciences it was possible to get access to two different milling machines. One was the DATRON M8Cube and the other was a noname milling machine. The DATRON M8Cube allowed using 20 mm to 0.1 mm drills, high-frequency spindles and it works with a concentric accuracy of the spindle of less than 2µm. The noname frame had much less accuracy, but a very large contact area. Unfortunately, because of the size of the procured plate, the DATRON milling machine dropped out. When it was possible to place the plate into the M8Cube, it could not be fixed. Therefore, the only possible way to get the plate milled was through the noname milling machine.

One of the biggest disadvantages of the milling machine was that there was no suitable exhaust system installed. In addition to that, the material which was to be processed was made of glass fibres. To avoid physical or health injuries, the person responsible for the milling machines decided to do the milling outside of a closed room using an industrial vacuum system, to vacuum the fibres and all other residues of the milling. Unfortunately, the milling was not as accurate as assumed. This might be due to the moving of the milling machine, the missing leveling of the machine before the milling had started, the inaccuracy of the machine or due to a fault while the template for the milling was adjusted. Despite the tight schedule and the plate which was much more expensive and far from satisfactory, these results were used to build the centre frame. Every part which was inaccurate was drilled subsequently to the correct dimensions. This was not the best way, but unfortunately the only possible way to handle the situation.

Figure 3-3 shows the centre plate in the used version. Fortunately, everything now fitted in where it should be. Both holders, from the carbon tube (the 3D printed and

the reused from the test centre plate) fitted perfectly into the milled centre plate. Therefore, the attachment of the arms of the copter was no problem either.



*Figure 3-32: Milled centre plate screwed together with the carbon tubes (own representation).*

### 3.3. Building of the Landing Gear

To make sure that the copter was also able to land in very rugged nature a suitable landing gear had to be built. Following the planning, the legs had to be attached to the copter. To achieve good compatibility of the used parts, the legs were also made from 18 mm CF tubes. To realise the calculated maximum size of the payload, the landing gear should lift the copter to at least 500 mm. For that reason, carbon tubes with a length of 500 mm were used. On one end, the legs were attached to an adapter to mount the tube to the copter. On the other side, there was a small 3d-printed bumper, that was used to be stuck into the CF tube. The adapter plate at the arms of the copter was also made of Curv. To hold the legs in the prepared adapter plates and the adapter plates itself onto the arms of the copter, the mounting parts from the test frame kit was used. Alternatively, it could be conceivable to print these attachments or drill some wooden parts. Therefore, a replica was also guaranteed. Figure 3-4 shows the mounted and attached parts of the landing gear.

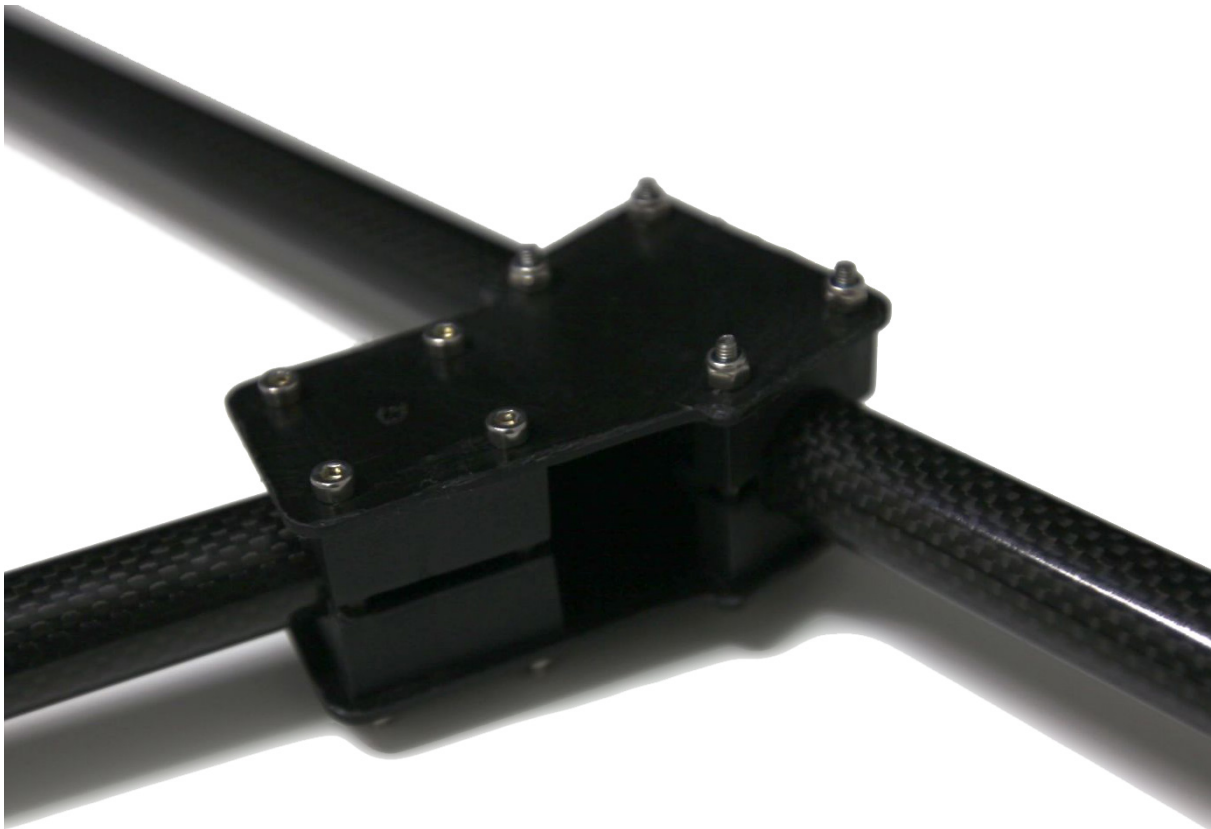


Figure 3-4: Attachment of the landing gear on the carbon tube of the arm of the copter (own representation).



### 3.4. Building of the Motor Holder

To complete the construction of the copter itself, the motor holders had to be built. As described in the planning phase, the motor should be fixed to an adapter plate which was attached to a housing for the electrics of the motor and the arm tube. Fortunately, the milling of the adapter plate was done by the second supervisor of this thesis. The plate was made of CFRP and had a strength of 3 mm. This was far too much as requested, but the adapter plates were made of residues from the workshop of the Technical University, therefore there was no other choice.

In addition to the adapter plate, the housing for the electronic components had to be built. As it was described in the development phase, the housing should be 3d-printed. To arrive at the point of a useful housing, many test prints needed to be carried out. This was due to the fact that the characteristics of printed material were very difficult to predict. Another reason was the permanent improvement of the housing. In the first version it was planned to secure the tubes and the power cords. A little protruding lip was used to ensure the housing was waterproof. Due to the movement of the ESCs from the centre plate into the motor holder housing it was necessary to enhance the space available in the inner of the housing. At the same time, it was to make sure that the housing did not exceed the maximum dimensions of the motor. In order to ensure that every restriction was complied, the size of the enclosure was changed in height. This allowed to place the ESC with a special adapted 3d-printed holder upright at the carbon tube in the inside of the enclosure. The upright position of the ESCs allowed placing heat sinks at the ESCs. This should become important later on.

#### 3.4.1. Re-Design of the internal ESC Holder

In the following tests with the ESCs it was necessary to change the ESCs to another model. This was due to the bad results of the calibration of the ESC-Motor combination. The new ESCs (Air40) had slightly changed dimensions. This required changing the ESC-holder in the inside of the motor holder's enclosure. The housing itself was big enough. For the design of the Air40 ESC holder see figure 2-11.

The new ESC also required changing the position of the ESC. In the next generation of the ESC-holder, the ESC should be laid down. This was because the new ESC had a large heat sink at one side. In addition, the test results with this ESC demonstrated the

high ineffectiveness of the new ESCs. The now emitted heat had to be dissipated. This was done by an additional heat sink which was glued<sup>43</sup> directly onto the ESC. Furthermore, a copper sheet was placed between the two heat sinks, which was led to the outside and glued to the housing. At this point an additional heat sink was placed at the outside of the enclosure directly into the air stream. In specific tests this variation ensures a reduction of the heat accumulation.

### 3.4.2. Temperature Tests

In different tests the temperature of the ESC inside the housing, the temperature of the outside heat sinks, of the motor and the ambient temperature were recorded. In a test without any additional heat sink and an ambient temperature of 21°C this indicates a high rising temperature of the ESC while the motor was in operation. Unfortunately, this test could not be completed because the test had to be aborted to avoid an overheating of the electronics. The temperature at the point of termination was 70°C. It could be assumed that the temperature would rise further if the test was not stopped.

In the next test the experimental setup for the cooling was done as described above. In this test the temperature increased very slowly and still remained at 63°C. The temperature during which the test was carried out was at 21°C, the outer heat sink had a temperature of 23°C and the motor had a temperature of 80°C<sup>44</sup>. This result was good enough to use this heat dissipation. Therefore, the development of the housing could be continued.

### 3.4.3. Installation of the ESC Cooling Option

After every part was placed in the inside of the enclosure the power cords to the motor had to be led to the outside. To make sure that this progress did not violate the waterproofness of the housing a little separate housing was developed, which was attached

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<sup>43</sup> Naturally a special thermal conductive glue was used. This glue was based on urethane methacrylate. This type of glue cured under exclusion of air by time. It allowed a continuous heat of at least 150°C and had a thermal conductivity coefficient of  $0.1 \frac{W}{(m \cdot K)}$  (ASTM C177) [95, 96].

<sup>44</sup> This very high value suggested, that the ESCs and the motor also did not work well. This could suggest that the configuration or the timing of the ESCs was set wrongly. Normally the motor should not have a temperature of over 50°C [42].

to one side of the big enclosure. This was due to the possibility to plug the motor easily to the ESCs or, if necessary, pull the plugs and remove the motor. The plugs and the opening of the housing were sealed with special sealant silicon [79]. To ensure that a waterproofness was also granted at the point where the carbon tube enters the housing and where the two parts of the housing plugged together, a silicone sealant was placed there too. At this point the housing was primarily ready. A change of the ESCs to the AutoQuad ESC32v3, which had been implemented later on did not affect this development. This was because the ESCs in the version 3 had the same dimensions as the ESCs in the version 2. Therefore, the already printed parts could be used and no additional components had to be constructed.

### 3.5. Building of the Universal Mounting System

In the next step, the universal mounting system had to be built.

To implement this, the different acrylic plates had to be cut as required. It seemed that the easiest, fastest and most accurate way to do that, was to cut the pieces with a laser cutter. Thankfully, the ViNN:Lab of the Technical University of Applied Sciences provided the access to a cameo Epilog Zing 24 laser cutter [82]. This laser cutter allowed it to cut different materials with a laser [83].

#### 3.5.1. Flexible Servo Arm

The servo arm itself should be made of acrylic glass.

##### *Cutting*

For the first application it was required to cut high-quality casted acrylic glass with a thickness of three and four millimeter. As planned these five plates were cut off. The Epilog Zing 24 gives the advantage of 100 % perfectly fitted mounting arms. This was due to the high precision of the laser cutter which had a repeat accuracy of 0.0127 mm [83]. The mounting arms were constructed using a PDF<sup>45</sup> template, which was generated with Adobe Illustrator. The cutting was done with presets for 3 mm respectively 4 mm plates. The cut parts had an overall thickness of 18.05 mm. Therefore, there was hardly any of the feared scattering of the thickness—more specifically, they counterbalanced themselves. In any case, these results were very satisfactory. As the parts were cut and screwed together, it was noticeable that the outer plates only had the purpose to hold the shovel. This made it possible to reduce the mass. In the next step the outer plates were cut to a minimum size—from previously nearly 350 mm to a short 82 mm. The additional cutting resulted in a new mass of 7 g. In comparison to the old mass this was a mass reduction of 13 g for each plate, resulting in an overall mass reduction of 104g for eight plates—a huge improvement for a simple cut-off.

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<sup>45</sup> PDF = portable document format

To make sure that the servo arm got in contact with the mounting-arm, the top plate pointing to the servo was provided with a recess. This recess was exactly made for the dimensions of the servo-arm. Because the servo-arm was higher than one plate, the plate in the middle of the mounting-arm had to be adjusted. Now the servo-arm was fitting perfectly to the mounting-arm. To increase the contact surface it was decided to cut the exact same part of the 3 mm plate, as done before with the 4 mm plate, and glue [82] it to the recess of the 4 mm plate. This operation ran without any problems. After the acrylic glue was cured<sup>46</sup>, a stress test was carried out. The results of the tests were positive and most of the operations were passed, that is until the mounting-arm broke. The load on the mounting-arm was almost 6 kg. After the test was aborted, the reasons for the damage of the arms became clear. The acrylic glue effected the material and led to small 2 mm cracks. This was an indication for a high internal tension of the plate. After more research it became clear that the plates had to be annealed<sup>47</sup> after glueing.

### *3D-Printing*

In the next step the designed 3D parts had to be printed. The very long and complex procedure of the printing made this very work-intensive. This was mainly due to the experimental system.

The 3D printer was also made available by the ViNN:Lab. The used printer for the small parts—up to 20 mm edge length—was the MakerBot Replikator X2 [80]. This printer provides the opportunity for PLA<sup>48</sup> or ABS printed objects [83].

The parts which had to be printed for the flexible mounting arm were the shovle and the arm- and servo-holder. For each arm four parts had to be printed. As already described in the development part, the arm- and servo holder consisted of three parts. One big locking part and two identical mounting parts for the locking on the copter-

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<sup>46</sup> The glue was curing with UV-light [84]. As there was no UV-lamp available, the part was put directly out in the sunlight after gluing. For this reason, the curing time increased to more than three hours, because the intensity of the UV radiation was not as high as a dedicated UV-lamp.

<sup>47</sup> Detailed information about the annealing can be found in the description of the construction of the fixed-arm.

<sup>48</sup> PLA was just available after an additional cooling fan upgrade.

arm tubes. The small and simple structured tube mounting parts were printed quickly. The printing of the parts which were much more complex in their structure, like the arm- and servo-holder or the shovle, was very complicated. Due to the structure and the size of the parts the printing often stopped. This resulted in a great number of misprints and a lot of wasted material. This was an immense factor for the increase in costs and amount of time needed. However, in want of alternatives the prints had still to be done. Since the servo- and arm-holder had been printed, attempts were made to mount the servo into the holder. This attempt resulted in a broken servo-holder, because the printing result was not as exact as expected. To avoid further potential damage of the parts already printed, it was tried to increase their stability.

#### *Follow-Up Treatment of 3D-Printed Parts*

A mechanism to make the parts more solid was to vaporize the parts with acetone. To allow a continuous steaming of the parts in a closed enclosure, a small box with a bowl filled with acetone was built (circa 1 cm high). A grid with a perforated aluminium foil was placed over the bowl. The printed parts then had to be placed on top. The steaming was done in different successive procedures. In the first two tests, the parts were steamed for about five minutes at a subjective low concentration of acetone. Unfortunately, the results of that were not satisfying. Therefore, the parts were steamed with a higher concentration for about 30 minutes. This resulted in unusable deformed parts. For that reason, the very difficult printing process for these parts had to be repeated. To avoid further problems, the template of the servo-holder was slightly customized. It now was possible to mount the servo without damaging the holder regardless of how inaccurate the holder was printed. At least for the fixed-arm construction the lesson learned from these problems was to avoid 3D printings if possible.

The complete mass of the flexible arm was at around 145 g. Annex XXXIII shows the four completely cut and printed parts which already were put together.

#### **3.5.2. Fixed Servo Arm**

As mentioned, the fixed arm construction was made of one part allowing a high load capacity as well as a reduced mass. For the arm itself an acrylic plate with the strength of 12 mm was used.

### *Cutting*

This plate was also cut with the laser cutter mentioned earlier. As it was the first time at the ViNN:Lab that such a thick plate was cut it was risky to cut the plate without detailed knowledge of the procedure. Therefore, other FabLabs<sup>49</sup> and workshops were asked how to cut these types of plates. The most detailed information came from the offene Werkstätten. They provided a list of configurations for different materials for the laser cutter, which the ViNN:Lab also had in use. The information was provided by the Fabulous St. Pauli, itself also a FabLab. In line with the guideline from the offene Werkstätten, an acrylic plate with a thickness of 8 mm should be cut with a speed of 0.5 mm/s, a power of 100 % and a maximum frequency possible (5,000 Hz) [84]. A plate with a thickness of 15 mm should be cut with a speed of 0.3 mm/s and also 100 % power and frequency [84]. Unfortunately, the intended thickness was not specified in the list. However, this did not prove to be problematic. The list gave the indicative values for the cutting. In the next step, the plate had to be cut. Using the reference values, it was possible to find the best matching values with just a few test cuttings. It became clear that the parameters from the described 15 mm plate were nearly the same as for the 12 mm plate which would be used. To avoid problems that had occurred with the 3 mm or 4 mm plates, every part needed to be annealed after cutting.

### *Follow-Up Treatment of Cut Parts*

In order to absorb the stress in the inner of the plates the cut parts needed to go through the process of annealing. The manufacturer of the acrylic plates, EVIONIK, suggested annealing the glass following the cutting process. This annealing should be done in a heating cabinet at 80°C [85]. The annealing time can be calculated as follows: the material thickness in millimetres (mm) divided by 3 corresponds to the annealing time in hours [85]. In any case, the annealing should last for a minimum of two hours. The procedure took about 4 hours for the annealing itself and an additional four hours for

---

<sup>49</sup> A FabLab is an open and democratic High-Tech-Workshop with the aim to provide the access to industrial production processes to allow the manufacturing of individual pieces as a private person [98]. Typically, a FabLab grants access to 3D printers, laser cutters, CNC-Machines, compactors, and milling machines [97].

the cooling period. After this process was completed, the acrylic arms were deformed by 1-2° along the entire length; however, it seemed that the arms increased in strength. When touched the arms felt very solid. Further tests should confirm this assumption.

Together with the milled parts, which were assembled with the centre plate parts, the fixed-mounting-arm was ready to be tested.

The built fixed mounting system is shown in annex XXXIV. The fixed arm has a mass of approximately 110 g.



### 3.6. Test phase

In the testing phase the characteristics of the craft and the mounting system were to be tested.

#### 3.6.1. Test of the Mounting Systems

The universal mounting system should be able to hold different parcels and goods. The flexible mounting system should be able to take loads with a mass of up to 1 kg whereas the solid mounting system is designed to take charges of up to 5 kg.

In order to verify the targeted figures at this point the different mounting systems were tested. The results of the test are shown in the following:

First, the flexible mounting system was tested. For that reason, the small servos were attached to the 3d-printed servo holder which in turn was attached to the carbon tube arm of the copter. Thereupon the cut acrylic plates —along with the ratchet mechanism and the 3d-printed shovel—were screwed together and plugged onto the servo. Unexpectedly, the system was very quiet in operation and the yawing was very low. This was due to the poor quality of the servo holder, which resulted in a grinding of the servo arm during the mounting. The power of the system was a little more than calculated (1.1 kg was tested successfully), but this could be ascribed to the grinding arms which led to a friction higher than normal and therefore the load on the servo was not as high as it should be. Because of the mixed results of the 3d-printed servo holder, a break or other malfunctions could occur.

To put the fixed mounting system in operation the mounting plates for the servo and the arm were attached to the arm of the copter. Then the servo and the mounting-arm were installed. Now first tests were carried out. The results were remarkable. Each arm was able to take a load of over 5 kg. The power transmission was also optimised compared to the flexible arm. It now was possible to share the load among five locking points. In a computer calculation done before, the only weakness apparent was when the servo gear wheel was placed in the plastic servo horn. During the following tests this vulnerability should be confirmed in the form of broken teeth of the servo-arm. This meant that all servo-arms would need to be replaced by aluminium-made servo-arms. However, at the moment of purchase the only servo-arm suitable and available

came from China at a price of about 20.00 EUR. This was far too much, but owing to the lack of alternatives it was purchased nonetheless. For further constructions an alternative should be found in order to lower production costs.

In a test with a servo horn made of aluminium everything worked fine. The system also should be able to absorb peak loads. A figure of the payload test is shown in annex XXXV. Nonetheless, both systems have weak points. This is on one hand the permanent power consumption of the system which increases with a higher load and, on the other hand, a considerable yawing of the arms which were attached to the servo. The latter could result in poor flying properties and—even worse—in the breaking of a gear in the gearbox. Each of the flaws could lead to a crash.

The fixation of the payload was unique and exclusively available for the control using a classical remote control. The function for opening and closing of the gripper system was assigned to the potentiometer of the RC. When the payload was set in position, the potentiometer was rotated to zero and the mounting system closed as fast as the potentiometer was turned. Now the payload was attached to the copter. In the position where the good should be released the potentiometer needed to be rotated to the maximum position resulting in the immediate falling down of the freight. To use this function also with the Android GCS the software needs to be modified slightly.

### 3.6.2. Testing the Flight Conditions of the Copter

In the following test of the motor and the ESC it became evident that the system made of high quality parts at an affordable price would have excellent flying characteristics.

In the first tests the FC and the ESCs worked very well and very fast. The motor also responded as fast as only possible. The power of the system was remarkable and exceeding the requirements. A maximum flight time measurement was not done, because for the test a 5 Ah LiPo was used which had less capacity than the planned one. Therefore, the recorded time would not be significant.

The only weak point of the system was the frame, i.e. the tubes of the frame. It was assumed that the vibrations of the landing gear and the insufficient stiffness of the carbon tubes were not as high as shown in the validation test. This resulted in a very

unstable behaviour when the motors started to rotate. The system was able to fly, however, the best performance and the full potential of the well-tuned parts would only be released when the vibrations and the stiffness could be raised to an acceptable level. In addition, the 3d-printed bumper, which had been plugged into the end of the carbon tubes of the landing gear, broke during a hard landing. This was due to an insufficient infill of the 3d-printed bumper. Further versions should use a higher infill rate to increase the stability of this part allowing it to absorb peak loads better.

Controlling the copter with the tablet was as easy as expected. When the mobile device was connected to the internet, the maps were displayed very fast and clearly and everything that was required could be done. The built copter is shown in figure 3-5.



*Figure 3-5: Built and ready to fly UAV (own representation)*

The tape measure below the depicted copter shows an overall diameter of around 2,400 mm, measured from one end of the propeller blade to the opposite end of the propeller.

### 3.7. Financial Aspects

One major goal of the project was to find a transport solution that was affordable for aid organisations. For this purpose, the costs of the individual components were summarised (see table 3-1). Costs for bolts and nuts and other accessories needed for the building of the copter and the system are presented as a lump sum.

Table 3-1: Overview of the procurement costs for the UAV construction

Product	Quantity	Price (per piece)	Price (sum)
ABS-Filament ø 1,75mm, 1 kg - black	3	26,99 EUR	80,97 EUR
Acrylic glass black GS 600*300x3mm	3	8,90 EUR	26,70 EUR
Acrylic glass clear GS 500*250x4mm	4	6,00 EUR	24,00 EUR
Acrylic glass clear GS 500x250x12mm	1	23,09 EUR	23,09 EUR
AutoQuad ESC32v3	4	55,00 EUR	220,00 EUR
AutoQuad GPS antenna shield	1	14,75 EUR	14,75 EUR
AutoQuad M4	1	123,75 EUR	123,75 EUR
Carbon fibre plate 350x150x3 mm	1	41,90 EUR	41,90 EUR
Carbon fibre Tube 18x16x1000 mm	6	37,80 EUR	226,80 EUR
Curv polypro. plate 1000x497x2mm	1	15,00 EUR	15,00 EUR
Glass fibre FR4 plate 1000x500x4 mm	1	69,90 EUR	69,90 EUR
GPS external Antenna 35mm x 35mm	1	16,90 EUR	16,90 EUR
Graupner HoTT SMART-BOX (opt.)	1	39,85 EUR	39,85 EUR
Graupner MX-20, 12 Ch. HoTT (opt.)	1	395,99 EUR	395,99 EUR
HobbyKing Digital Servo 60g/31kg	4	44,31 EUR	177,24 EUR
LiPo protection Box	1	13,75 EUR	13,75 EUR
MTTEC KETO HV BEC V2	1	37,00 EUR	37,00 EUR
N4 expander for AQ M4	1	43,75 EUR	43,75 EUR
PLA-Filament ø 3,00mm, 2 kg - black	1	35,50 EUR	35,50 EUR
SLS APL 21000mAh 6S1P 22,2V	1	389,30 EUR	389,30 EUR
T-Motor Carbon Prop 29x9.5" (pair)	2	382,90 EUR	765,80 EUR
T-Motor U8 Pro KV170	4	243,90 EUR	975,60 EUR
Wires, plugs, bolts, nuts ...	1	150,00 EUR	150,00 EUR

Adding up all the costs yields a total of 3,907.54 EUR. This amount comprises only the costs for the required parts. If this UAV should be built, expenses for the staff, the premises and for the development should be integrated into the selling price. Therefore, the additional costs of the productions were estimated to the factor 1 of the hardware costs. Expenses for training were not included either. Under the premise of a low reselling price for aid agencies a price for the UAV of at least 7,815.08 EUR should be appropriate.

It is to be expected that a series production will cut the price to a certain degree.

Many parts of the UAV were printed individually. In the last project the time needed for the real 3d-printing was estimated<sup>50</sup> to a total of 104 hours needed to produce one set of functional 3d-parts for the developed UAV. This number does not include the various hours for the printing of the prototypes. Because of the many misprints the goal should be a professional production of the 3d-printed parts using professional injection moulding. With the production method currently used, the cost for the production would increase further.

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<sup>50</sup> A production waste of 50 % was assumed.

## 4. Discussion

The aim of this thesis was to examine the possibilities of supporting rescue tasks with an unmanned vehicle (i). On these grounds a market analysis was done and the technical requirements were established subsequently (ii). Then the planning, construction and testing of the vehicle were carried out (iii). Tests included examination of the performance, economic aspects and maintainability.

### 4.1. Conclusion

At the moment of the writing of this thesis, aid organisations were not able to help individuals. A survey which was done among charities showed that most of them do not have a solution to this problem. If an emergency affected a number of people that was too small, it was not efficient to help them.

Therefore, a solution was sought that would remedy this inability by means of a technical solution. On grounds of a few derivations, it was assumed that the simplest possible way to help aid organisations was to provide an easy-to-use transport solution. The aim was to enable charities to perform individual rescue operations without the need of special trained staff, the high use of funds and without a high expenditure of time. A market research was conducted to compare different existing products with the result being that there were no suitable products available or they were far too expensive. It was therefore determined that it was necessary to develop and construct an own transport solution. The solution should provide the ability of transporting a good within a range of at least 30 km and a weight of at least 5 kg. Furthermore, the vehicle should be able to also operate in rough weather and terrain. Therefore, the different types of transport vehicles were compared. For this task a UAV proved to be the most suitable. In the following, a UAV with two individual mounting systems was developed and constructed.

Retrospectively, the project of the development of a support transporter delivered good results. The possibilities of this copter are versatile. It can be expected that the FC-ESC-Motor combination works very well with the last of the most recent configuration. However, the flying performance of the UAV was not as good as expected.

The objectives of constructing an aerial transport vehicle that is easy to use have been fulfilled. This was done by a navigation and mission planning solution which allowed controlling the vehicle with a mobile device, like a smartphone or a tablet. For the aim of developing a mounting system for the transport of different types of payload two different mounting systems were developed. The first one was an individual one which was able to hold light parcels and also light bulky objects. This was realised by a second joint with a ratchet mechanism at the end of the arm. This allowed attaching a kind of a shovel of a conical shape. The second solution was designed to hold high weight parcels. It was shown that the copter was able to hold nearly every object of the size of 700 mm x 300 mm x 700 mm (WxHxD) and a mass of 5 kg.

The flight time should be reached with a low level of payload. Every part was covered and at least waterproof, therefore it could be assumed that the whole UAV should also be waterproof. With an assumed flight time of 45 minutes and a maximum speed of approximately 50 km/h the copter should be able to have a flight range of 37.5 km (PONR).

If a FC will be released in the future that natively supports a common rotor helicopter an increase of the payload and flight time should be possible. Until then, a Quadcopter solution should be the best in terms of costs and payload.

This proves that every requested point was achieved. The verification of the flight characteristics still remains outstanding.

## 4.2. Critical evaluation

The system which has been developed is rich in innovations. However, a couple of points have the potential for optimisation.

Unfortunately, the actual flight properties of the craft do not allow a review of the UAV's flight quality. In further studies the UAV should be optimised with regard to its flight characteristics. For further reviews the UAV should also be tested in and optimised for critical flight conditions. This could be done by using a more rigid frame or at least arms made of carbon tubes with a diameter of at least 25 mm. A landing gear with further vibration optimisations and a retractable construction could also improve the results.

Apart from the flight characteristics, the mounting systems need further research. The present system emitted strong vibrations and required a continuous electrical power supply. In case of a power failure in the mounting system, the UAV would open its arms and release the payload without prior notice. For such cases a motor with worm gears instead of a servo motor could be an alternative. At least the arms would not open and the copter would be able to transport the payload to its destination.

The requirement of the development of two mounting systems can also be called into question. Initially, it was considered important to have a mounting system for rectangular and also for bulky objects. However, it became clear that an easy construction and a preferably high force is more important than the possibility to hold bulky objects. When it is not possible to avoid the transport of bulky objects a solution would be to put the concerned goods in a box and attach it to the copter.

As the enclosure of the centre plate and in particular of the FC had not been completed within the timeframe of this thesis, other ways of production should be reviewed. Currently, it seems that the injection moulding was the only alternative to the 3D-printing method which was used for this project.

To enhance the security of the system, further developments should focus on an optical camera-based altitude control and a collision detection system.



If a setup as the described would be built and the plan was to use this copter in Germany many more fail-safe security features would need to be developed. These should include redundancy of the used components and an installation that minimises the consequences of an accident, such as a parachute or other kinds of a fall absorbers.

### 4.3. Summary

After the UAV had been developed and built, a transport quadcopter for individual support that was able to take high loads up to 5 kg was created. This copter is easy to maintain using simple replacement parts, such as wood, metal or comparable materials, and is under 8,000.00 EUR in acquisition. On top of that, the usage is very simple owing to the ability to control the UAV with a tablet or a smartphone. Besides that, it is also possible to control the system using conventional radio.

The development of the copter was made possible thanks to the use of very new and partly unreleased electronic components. Previous transport systems for UAVs do not support a load of such a magnitude and need at least special hard mounting points.

Moreover, it needs to be pointed out that this UAV is probably the first of these dimensions that allows the remote control using a mobile device.

This new type of UAV opens up many new opportunities for charities. However, this system is still very experimental and thus far away from series production. But aid agencies have to change their workflows progressively and should create use cases. Because this new type of transport system is sure to come, the only question being when.

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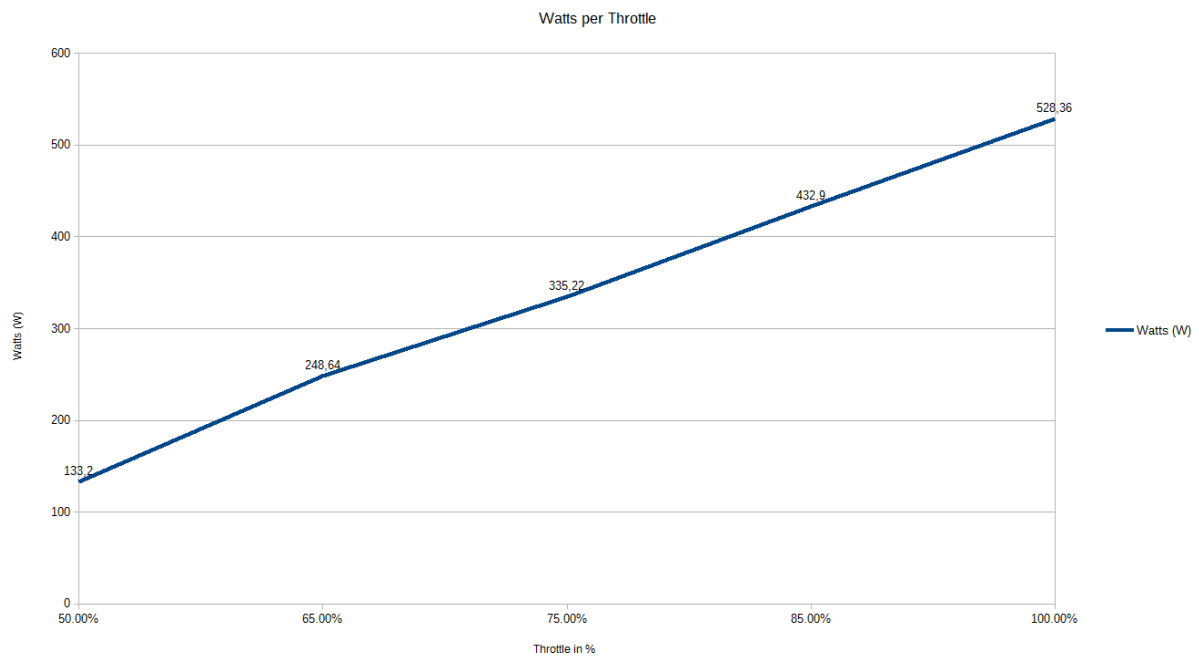
## Annex

## Annex I List of contacted aid organisations

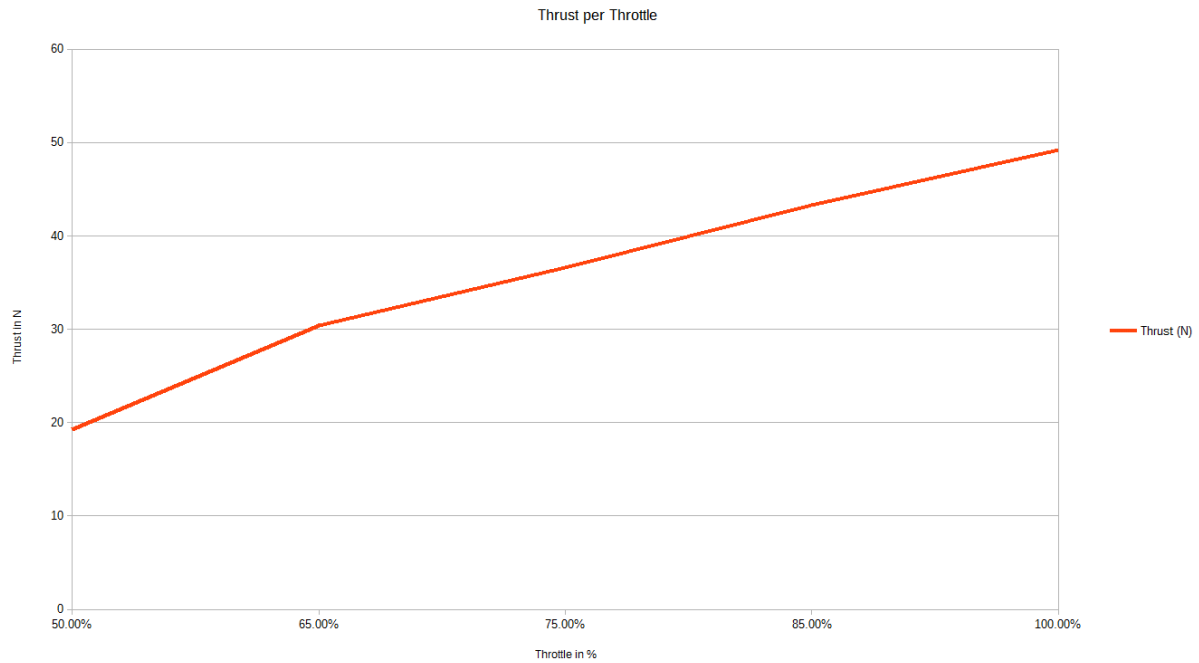
Aid Organisation	Contact address
Aktion Friedensdorf e.V.	info@friedensdorf.de
arche noVa - Initiative für Menschen in Not e.V.	info@arche-nova.org
Ärzte der Welt e.V.	info@aerztederwelt.org
Ärzte ohne Grenzen e. V.	office@berlin.msf.org
Bischöfliches Hilfswerk MISEREOR e. V.	info@misereor.de
Brot für die Welt – Evangelischer Entwicklungsdienst Evangelisches Werk für Diakonie und Entwicklung e.V.	kontakt@brot-fuer-die-welt.de
Bundesanstalt Technisches Hilfswerk (THW)	redaktion@thw.de
Deutscher Caritasverband e. V.	info@caritas.de
Deutsches Komitee für UNICEF e.V.	mail@unicef.de
Deutsches Medikamentenhilfswerk action medeor e.V.	bernd.pastors@medeor.de
	christoph.bonsmann@medeor.de
	dirk.angemeer@medeor.de
	ralf.deutzkens@medeor.de
Deutsches Rotes Kreuz e.V.	drk@drk.de
Diakonie Katastrophenhilfe – Evangelisches Werk für Diakonie und Entwicklung e.V.	service@diakonie-katastrophenhilfe.de
German Doctors e.V.	info@german-doctors.de
Geschenke der Hoffnung e. V.	info@geschenke-der-hoffnung.org
Hammer Forum e.V.	knossalla@hammer-forum.de
	info@hammer-forum.de
Malteser Hilfsdienst e.V.	malteser@malteser.org

<b>Oxfam Deutschland e.V.</b>	<a href="mailto:info@oxfam.de">info@oxfam.de</a>
<b>Plan International Deutschland e.V.</b>	<a href="mailto:info@plan-deutschland.de">info@plan-deutschland.de</a>
<b>Reporter ohne Grenzen e.V.</b>	<a href="mailto:kontakt@reporter-ohne-grenzen.de">kontakt@reporter-ohne-grenzen.de</a>
<b>SOS-Kinderdorf e.V.</b>	<a href="mailto:info@sos-kinderdoerfer.de">info@sos-kinderdoerfer.de</a>
<b>UNO-Flüchtlingshilfe e.V.</b>	<a href="mailto:info@uno-fluechtlingshilfe.de">info@uno-fluechtlingshilfe.de</a>
<b>World Vision Deutschland e.V.</b>	<a href="mailto:info@worldvision.de">info@worldvision.de</a>

## Annex II      Chart of T-Motor U8 Pro KV170 watts per throttle relation (own representation)



### Annex III      Chart of T-Motor U8 Pro KV170 thrust per throttle relation (own representation)



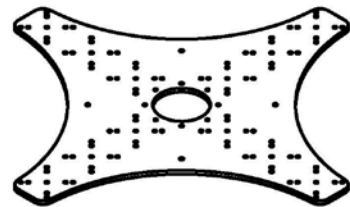
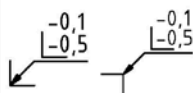
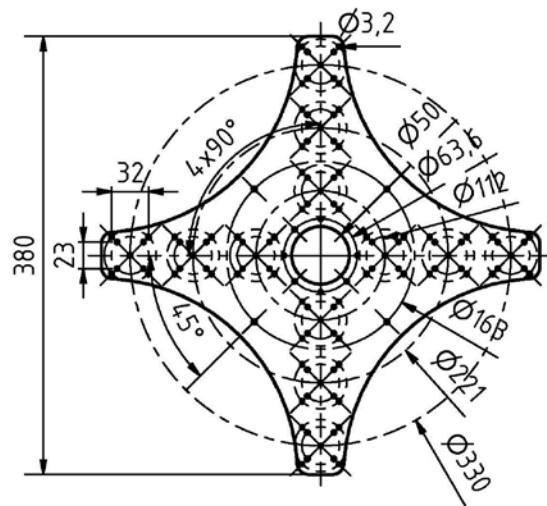




## Annex IV Drawing derivation of the centre plate

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



Scale 1 : 5		Developer C. Sponholz	Document type Drawing derivation	Document status Development version		
 Hochschule für Technik und Wirtschaft Berlin University of Applied Sciences	Implementation S. Marksches	Title Centre plate	Material		Mass	
			Date 17.07.2015	Language en	Sheet 12 / 26	

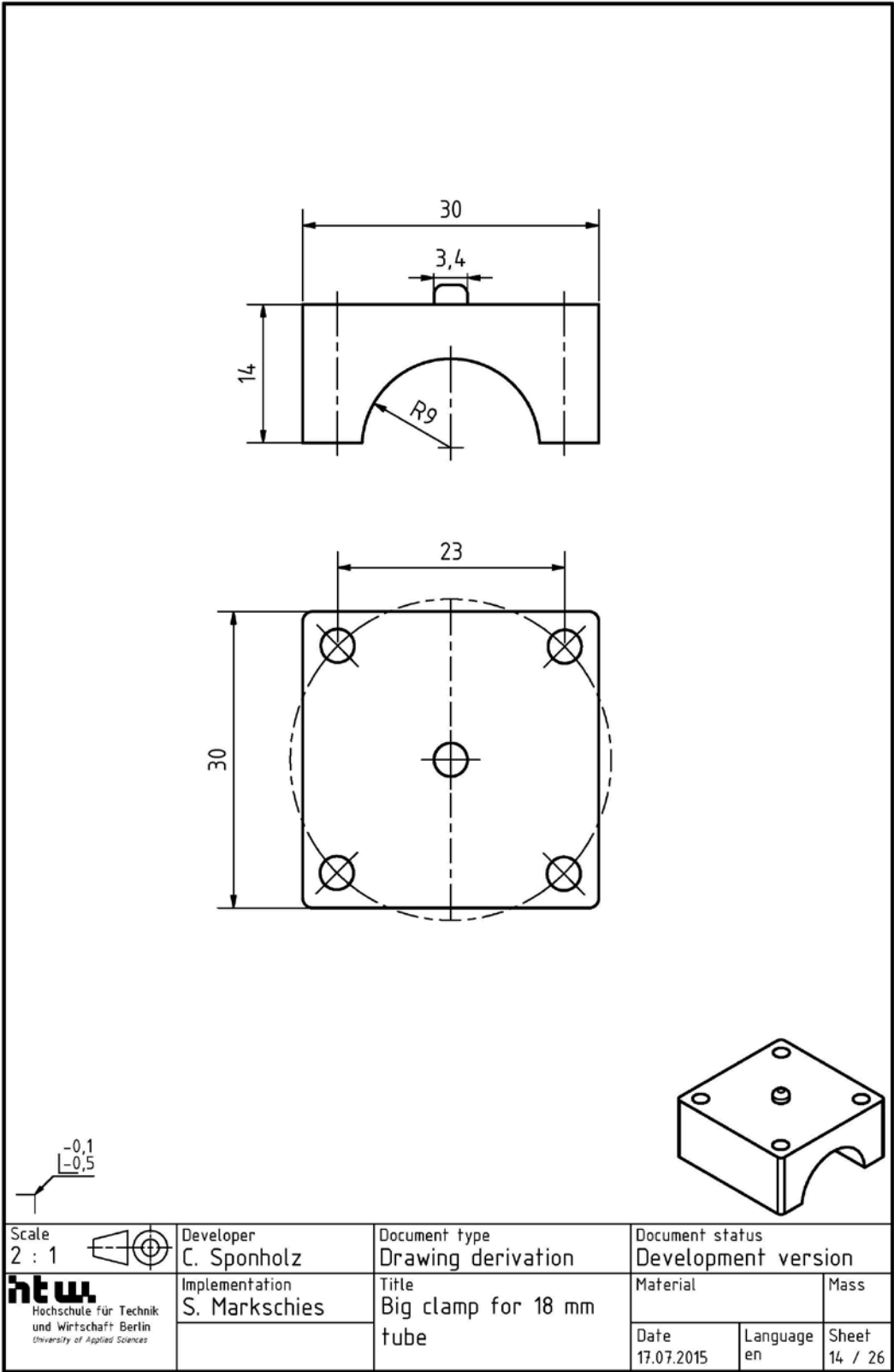
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex V Drawing derivation of the big clamp for 18 mm tubes

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



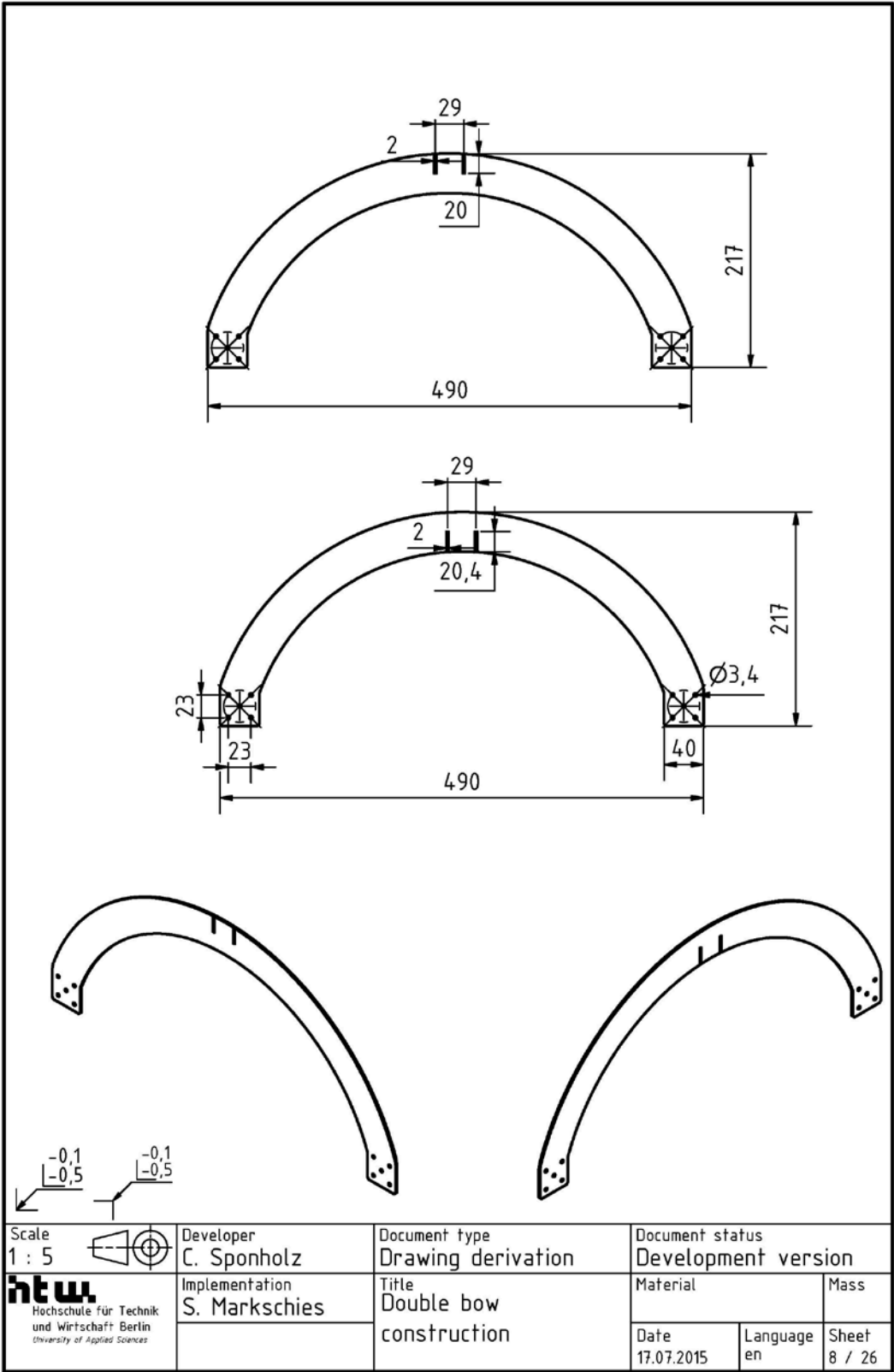
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex VI

Drawing derivation of the double bow construction

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



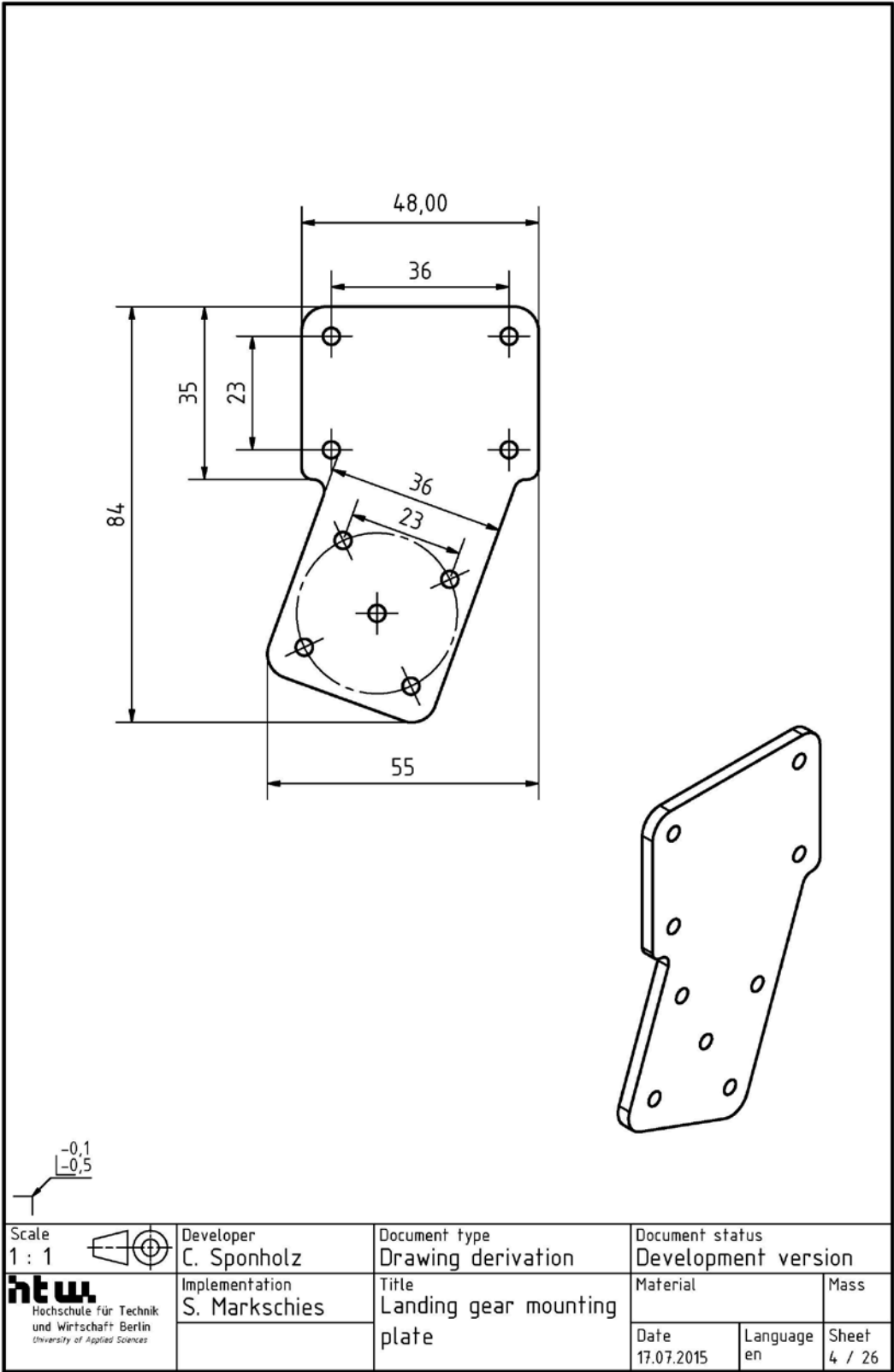
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex VII      Drawing derivation of the landing gear mounting plate

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

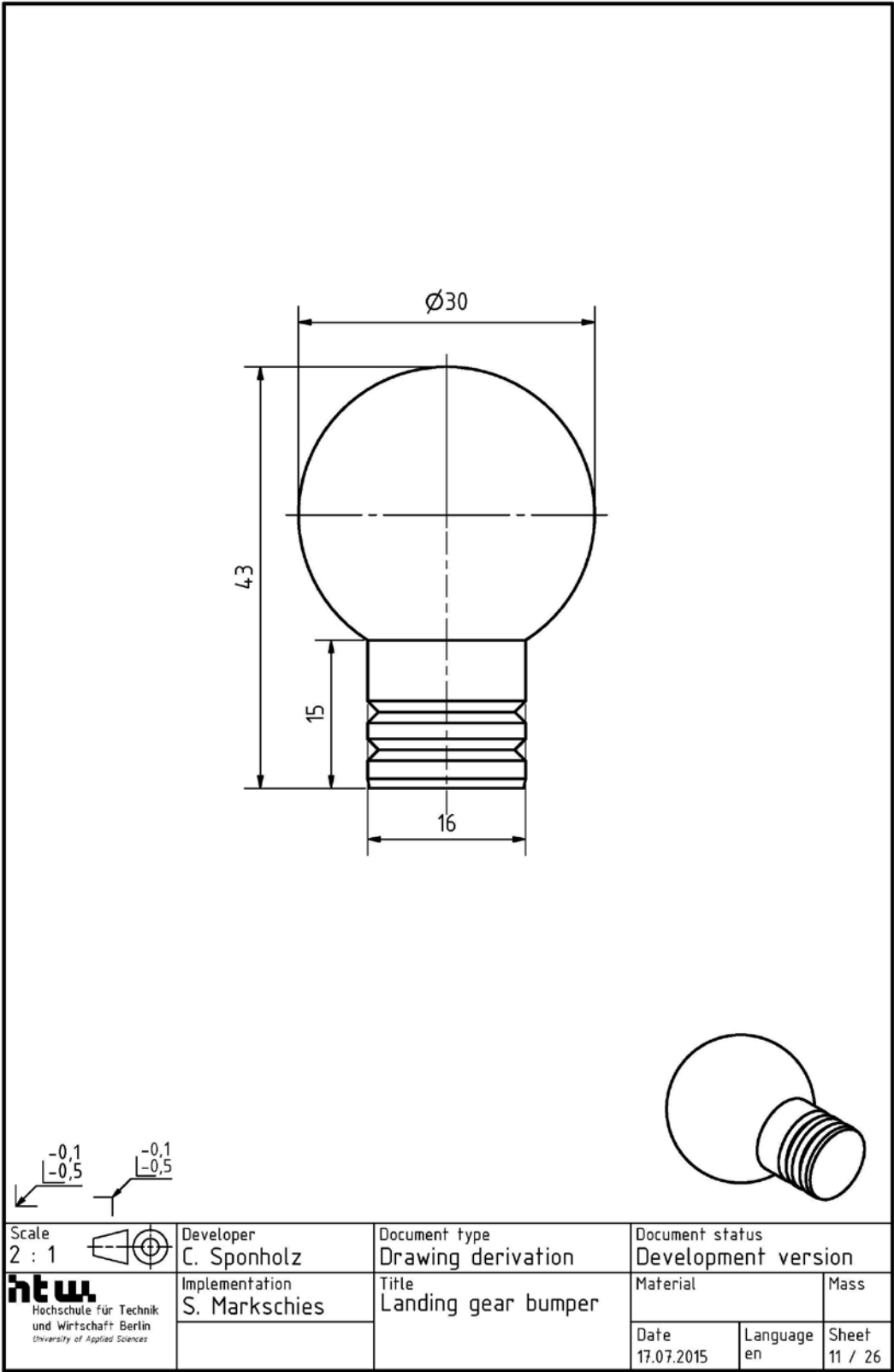
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex VIII      Drawing derivation of the landing gear bumper

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



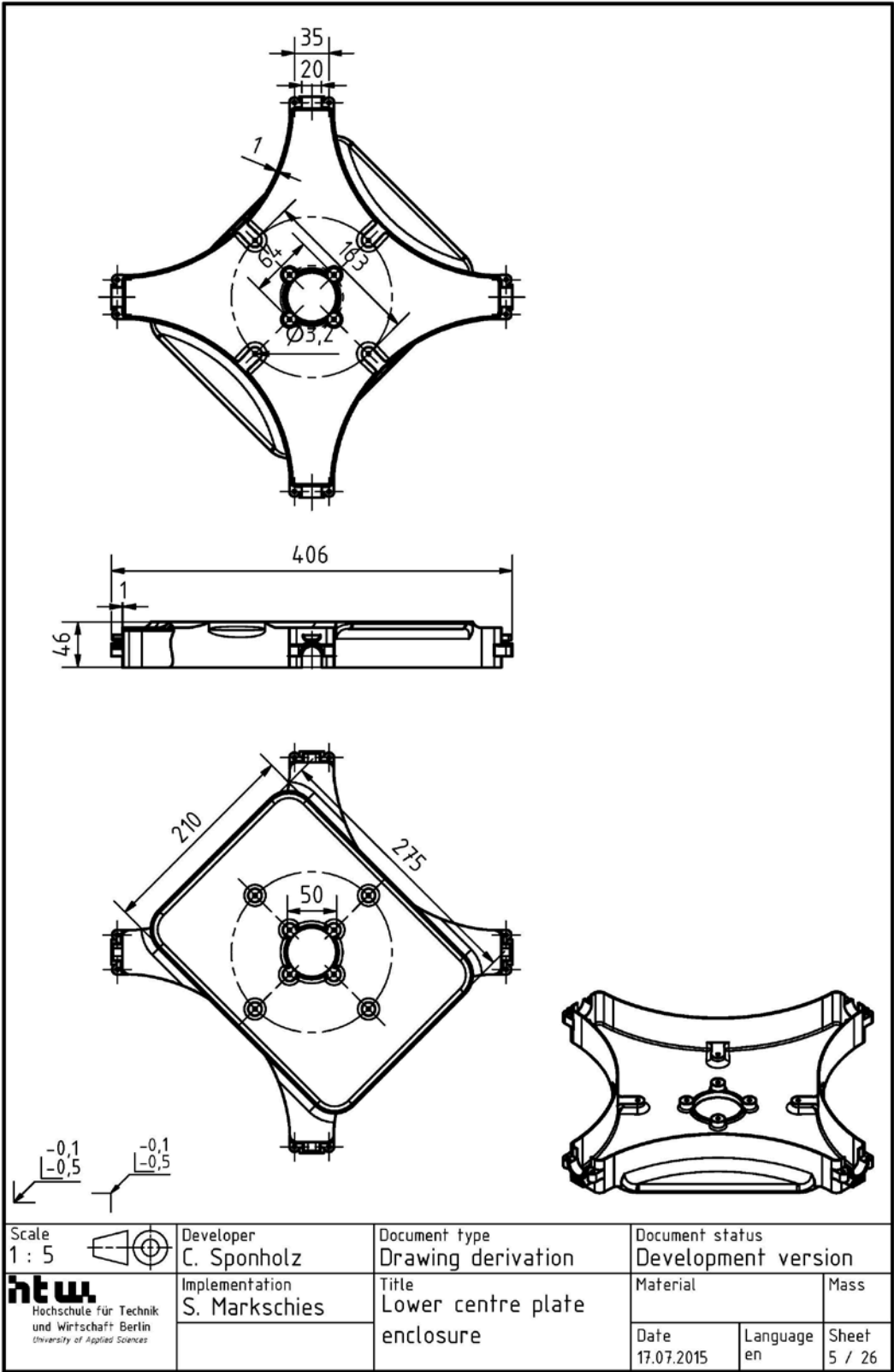
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex IX

Drawing derivation of the lower centre plate enclosure

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

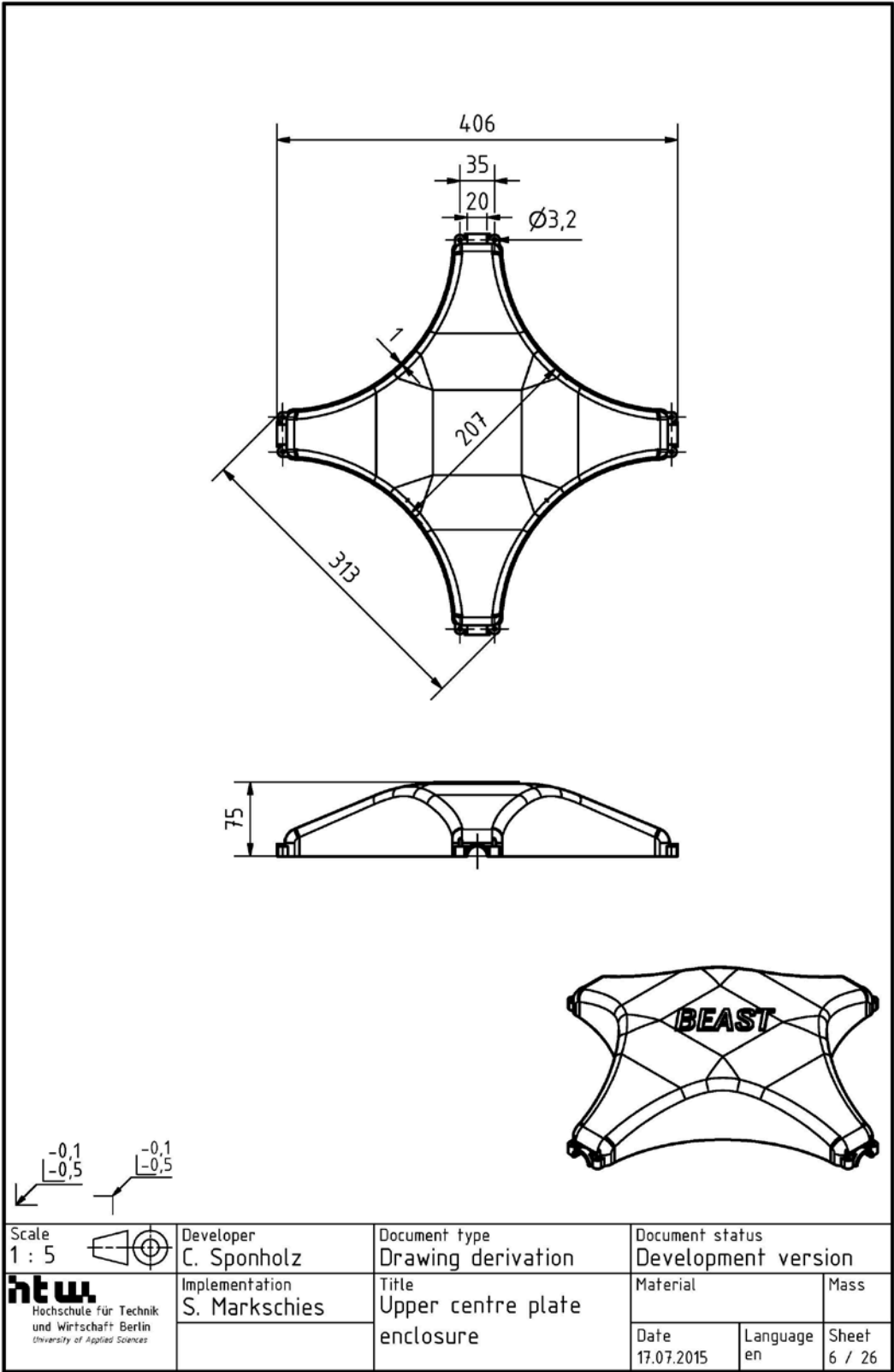
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex X Drawing derivation of the upper centre plate enclosure

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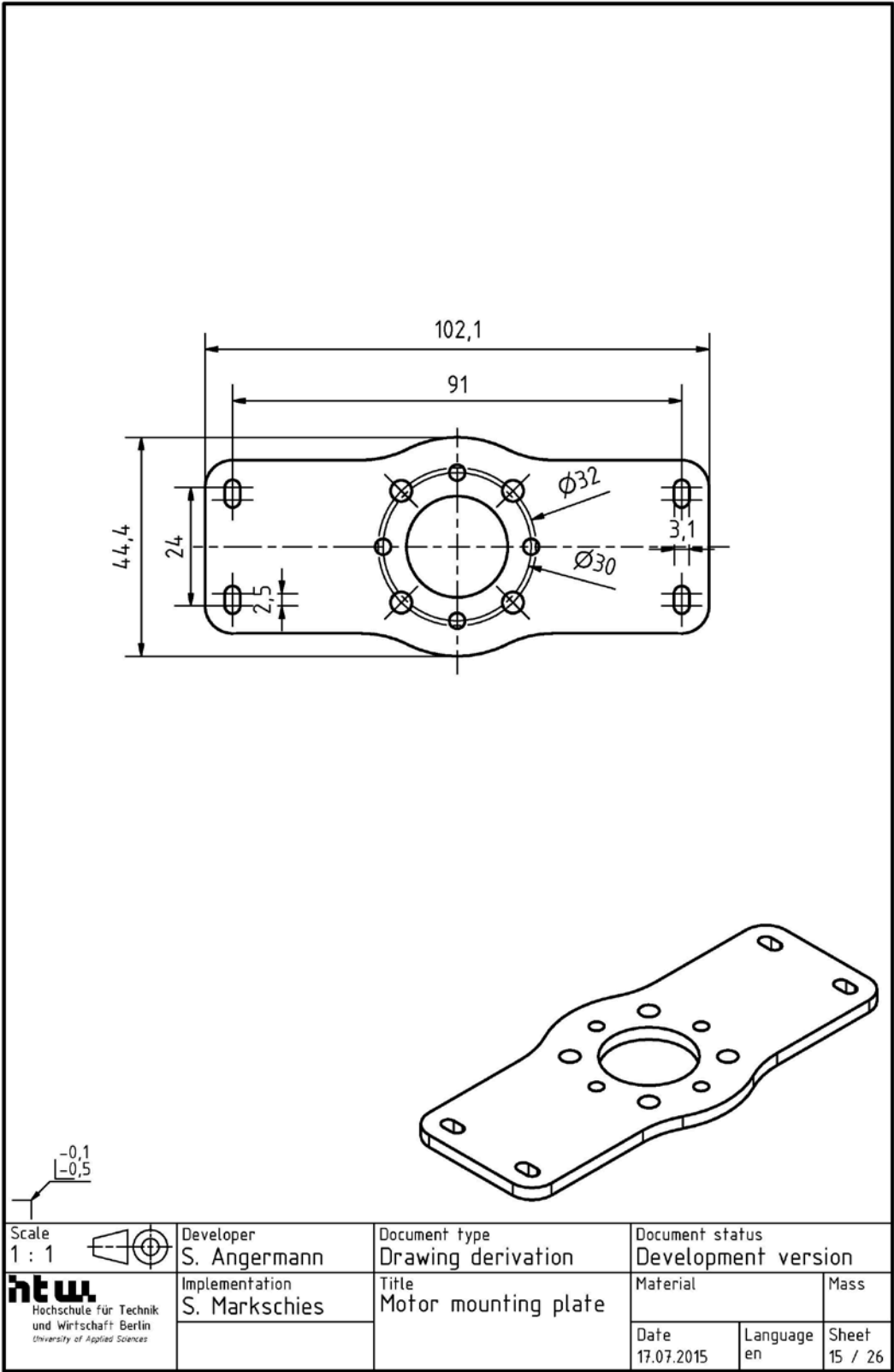
Annex XI

Drawing derivation of the Motor mounting plate

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



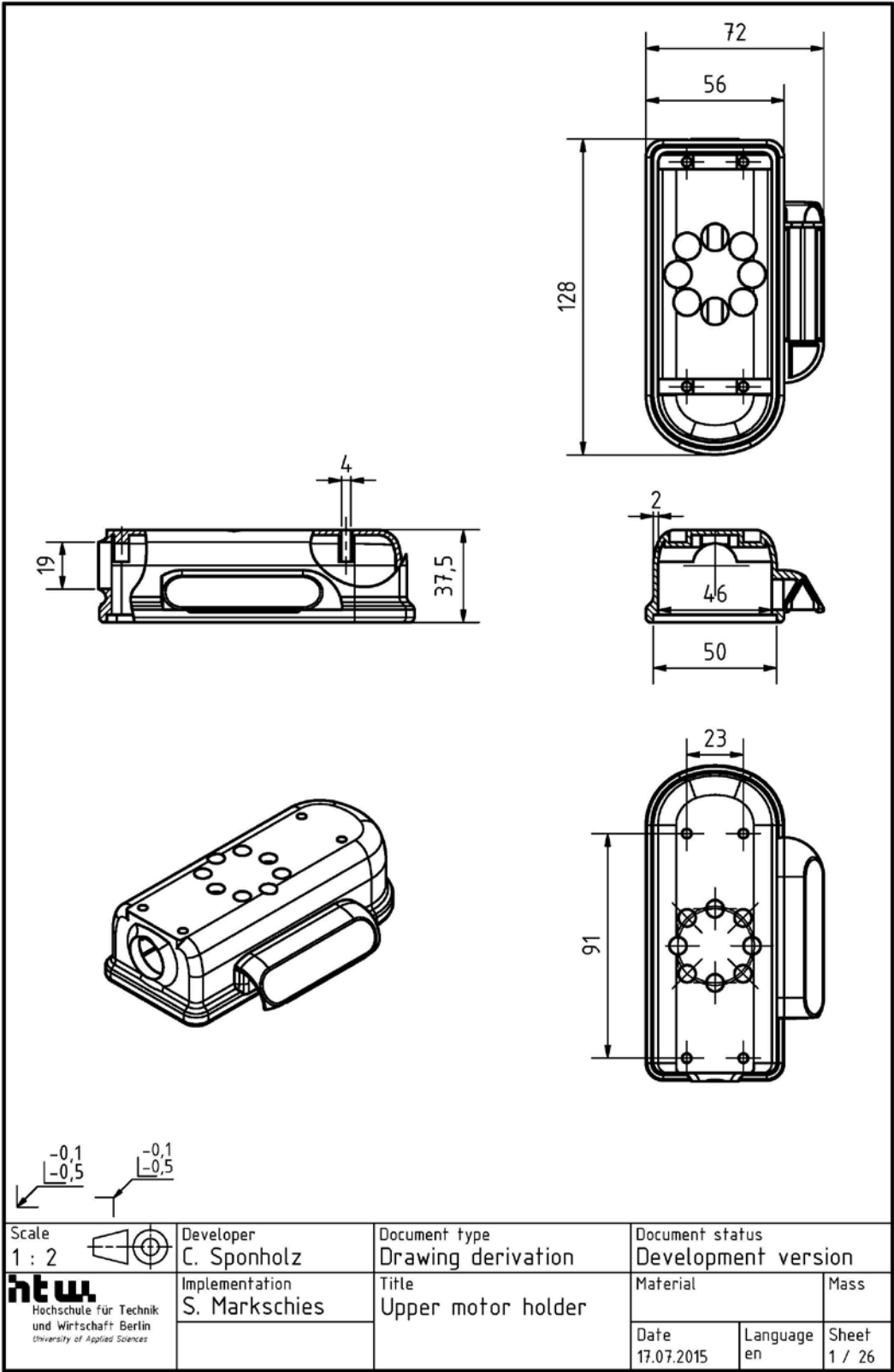
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



Annex XII      Drawing derivation of the upper motor holder

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VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



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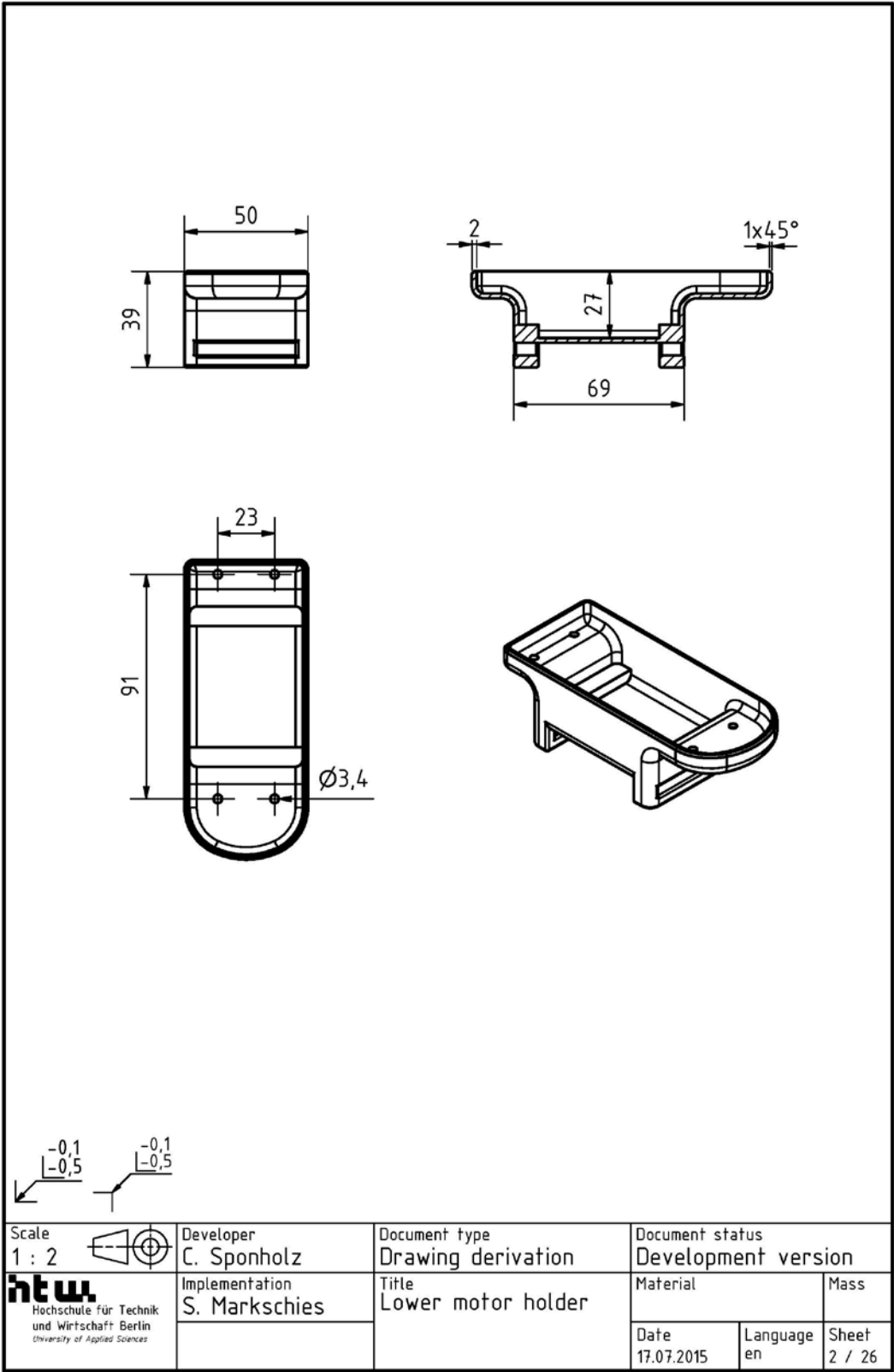
Annex XIII

Drawing derivation of the lower motor holder

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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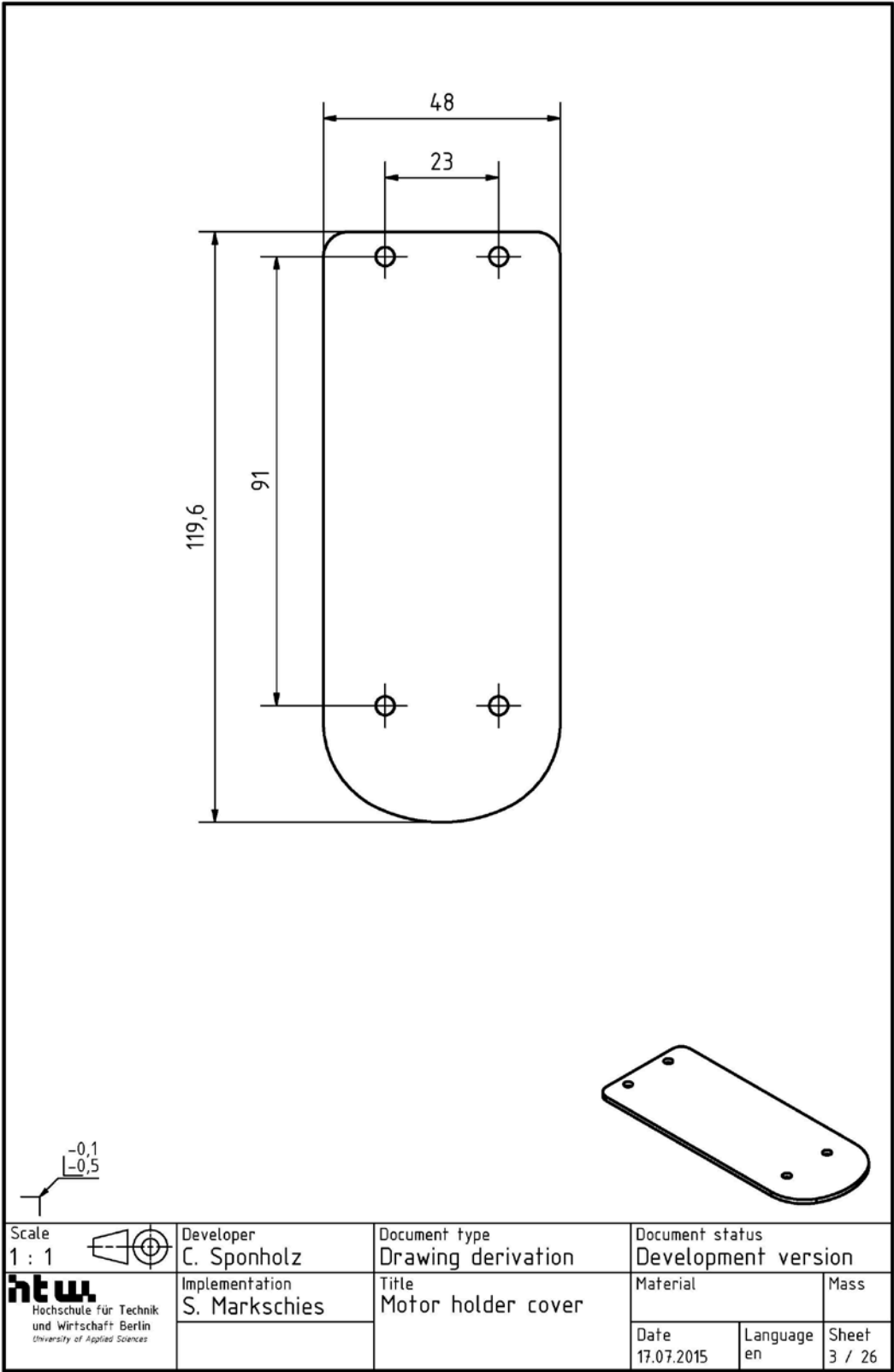
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex XIV      Drawing derivation of the motor holder cover

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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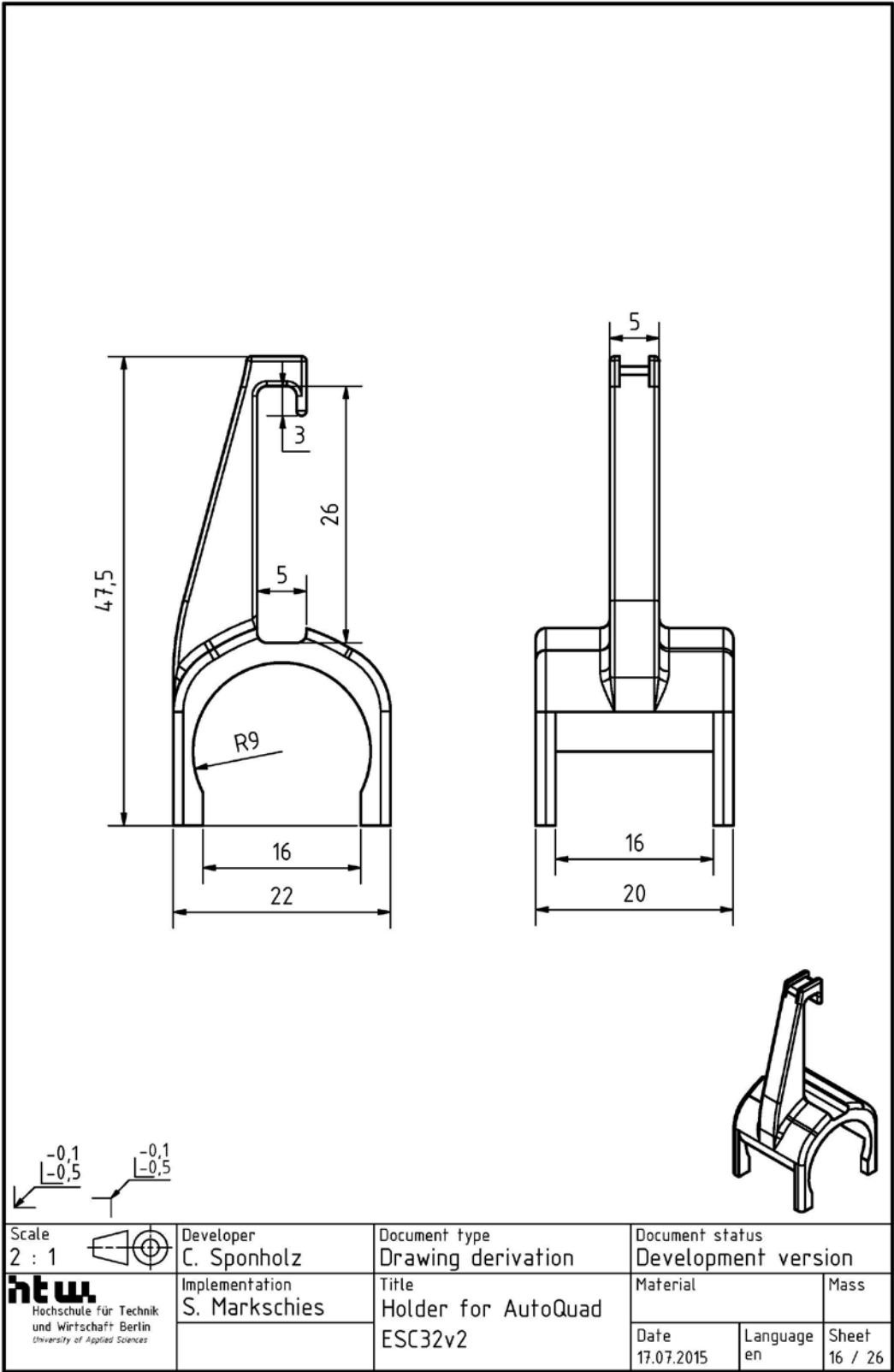
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Drawing derivation of the AutoQuad ESC32v2 holder

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



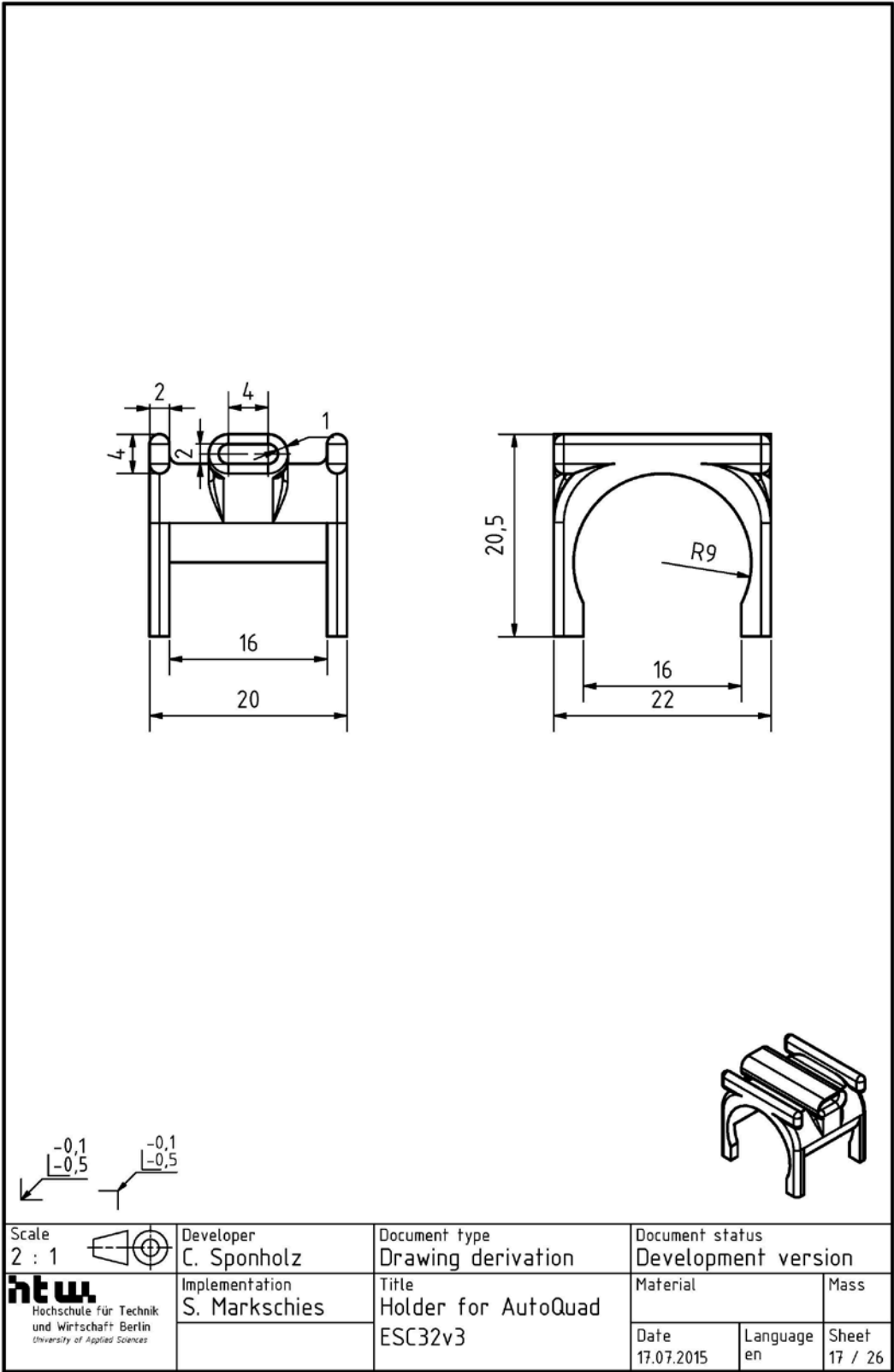
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex XVI      Drawing derivation of the AutoQuad ESC32v3 holder

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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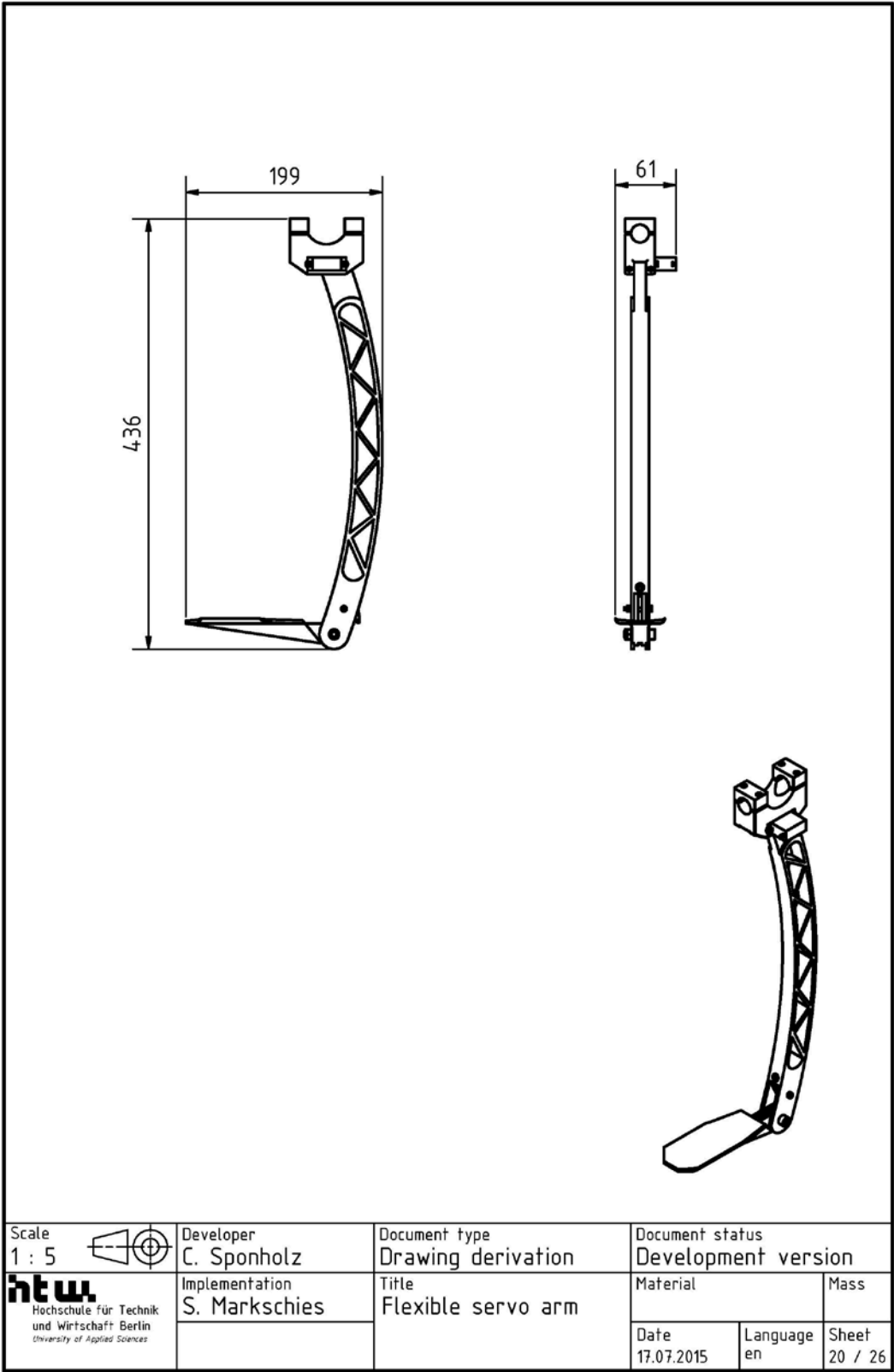


VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex XVII    Drawing derivation of the flexible servo arm

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

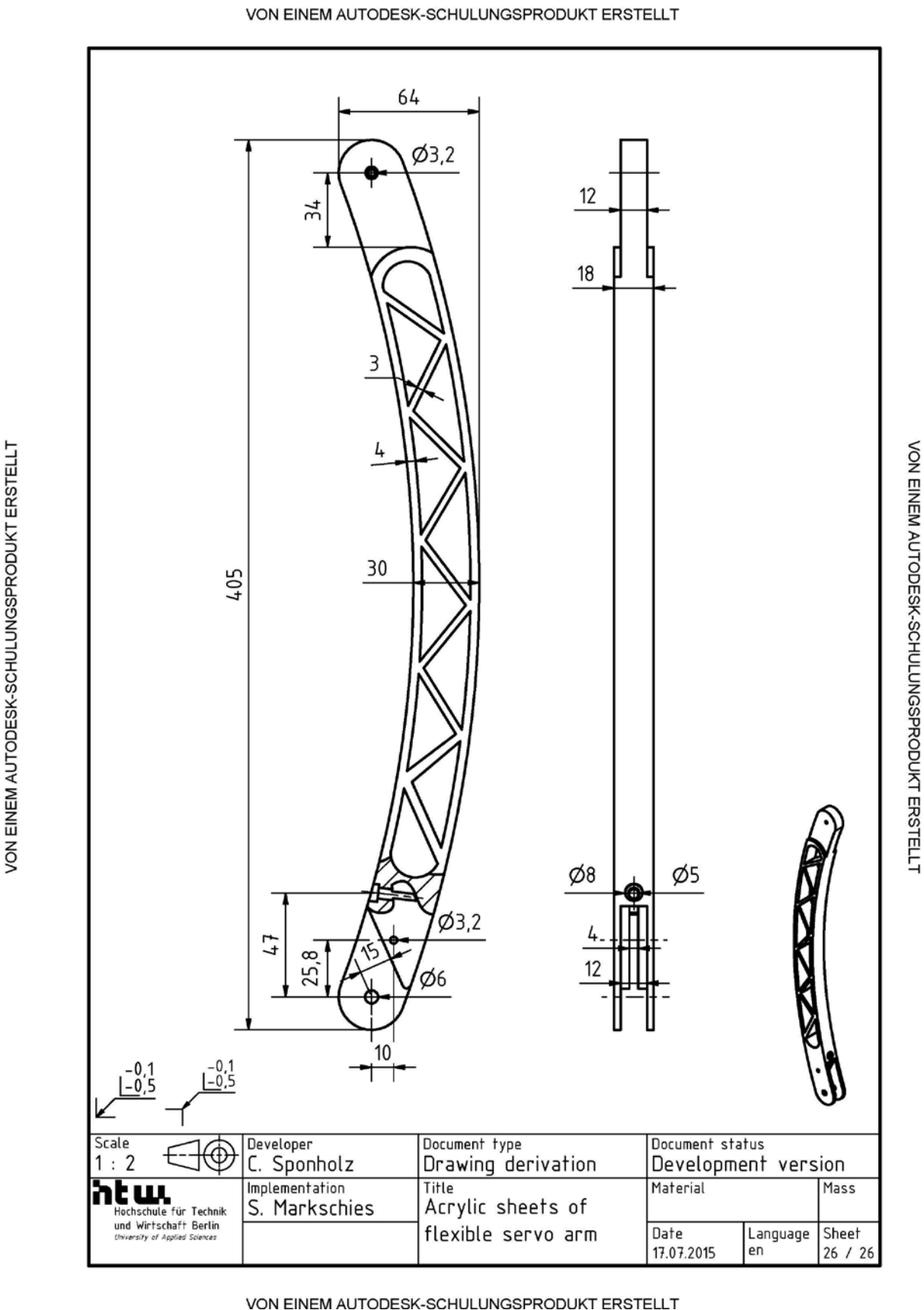
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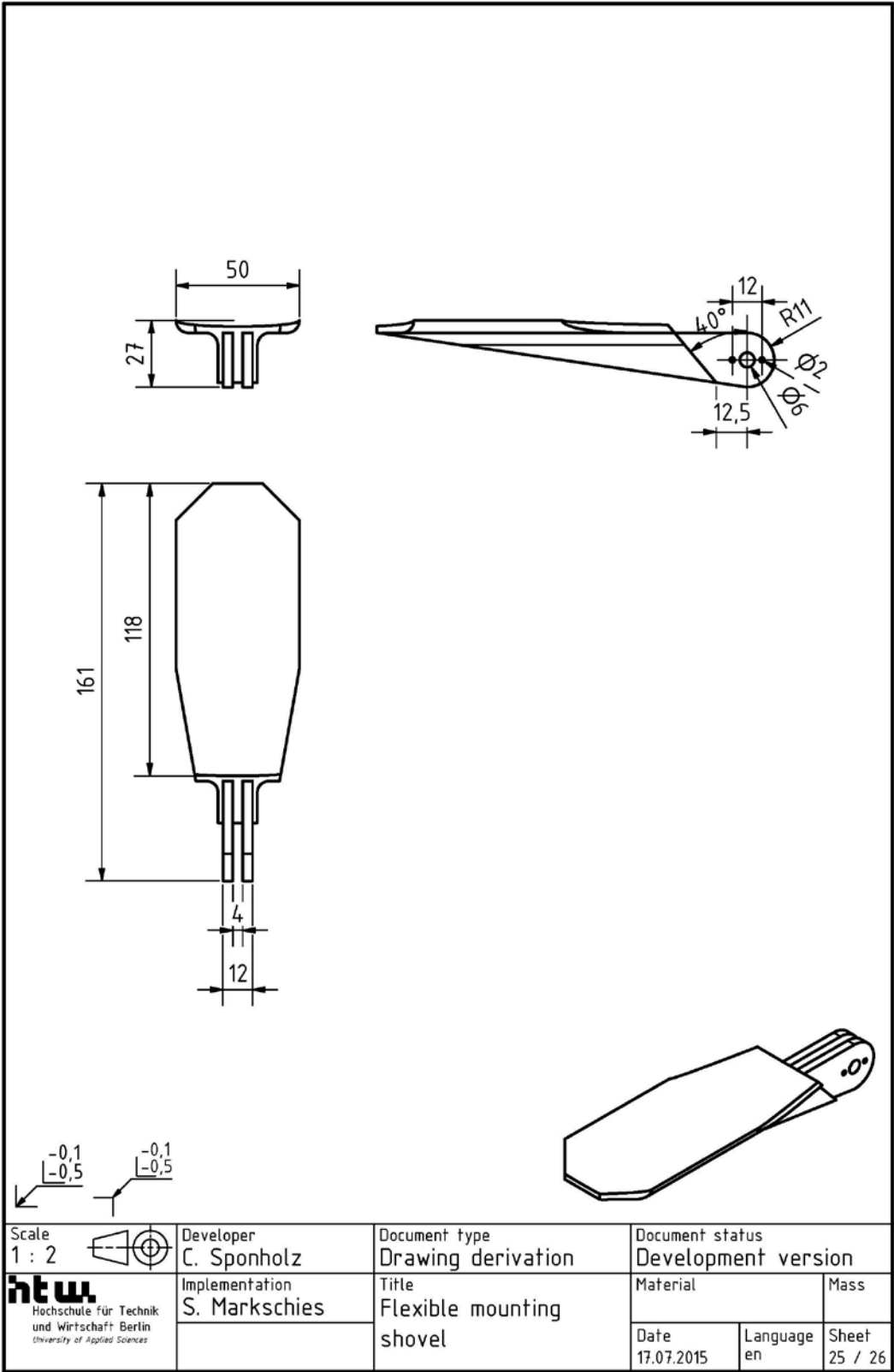
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Annex XIX      Drawing derivation of the payload shovel of the flexible servo arm

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



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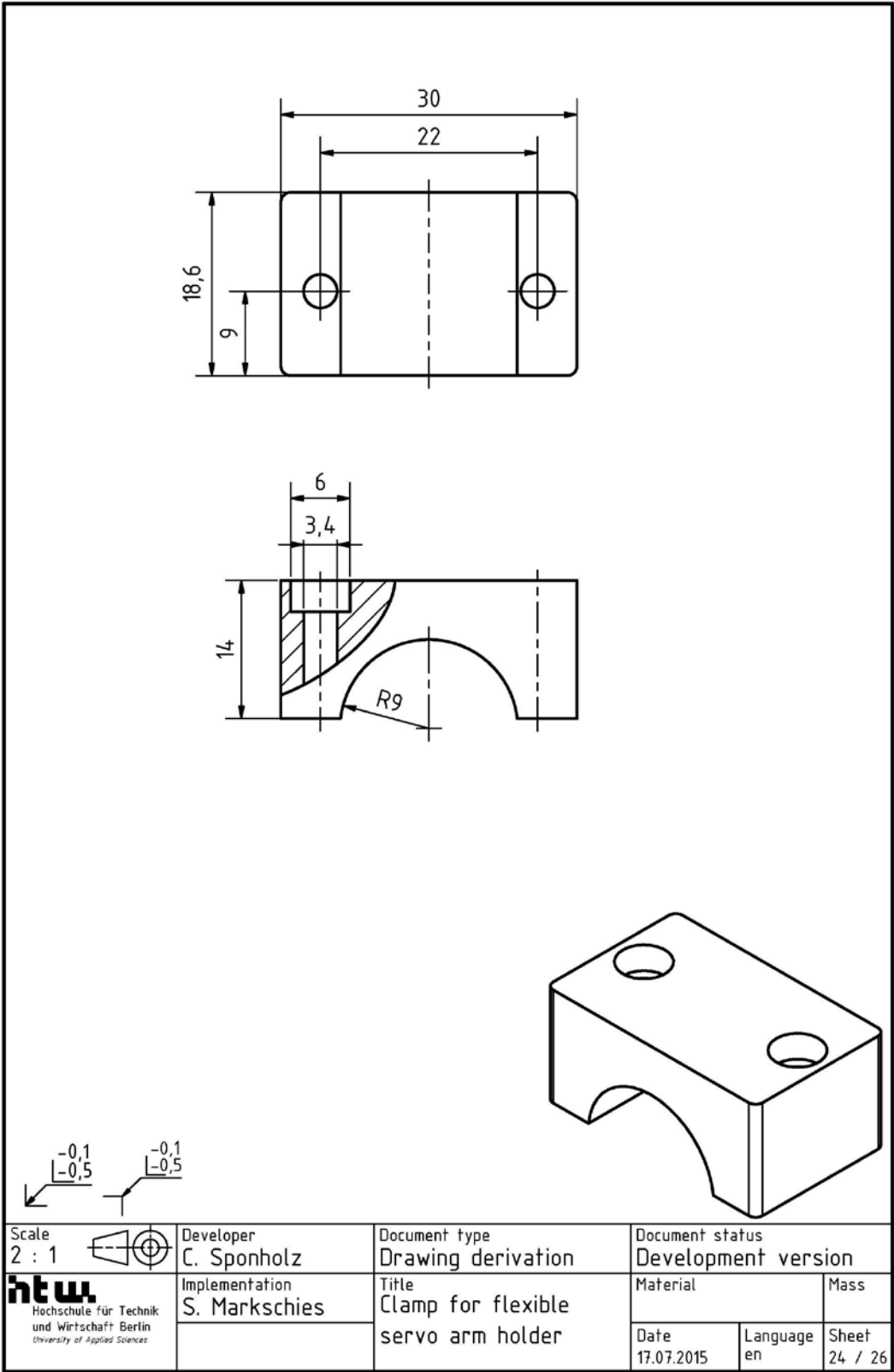
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Drawing derivation of the servo holder clamp of the flexible servo arm

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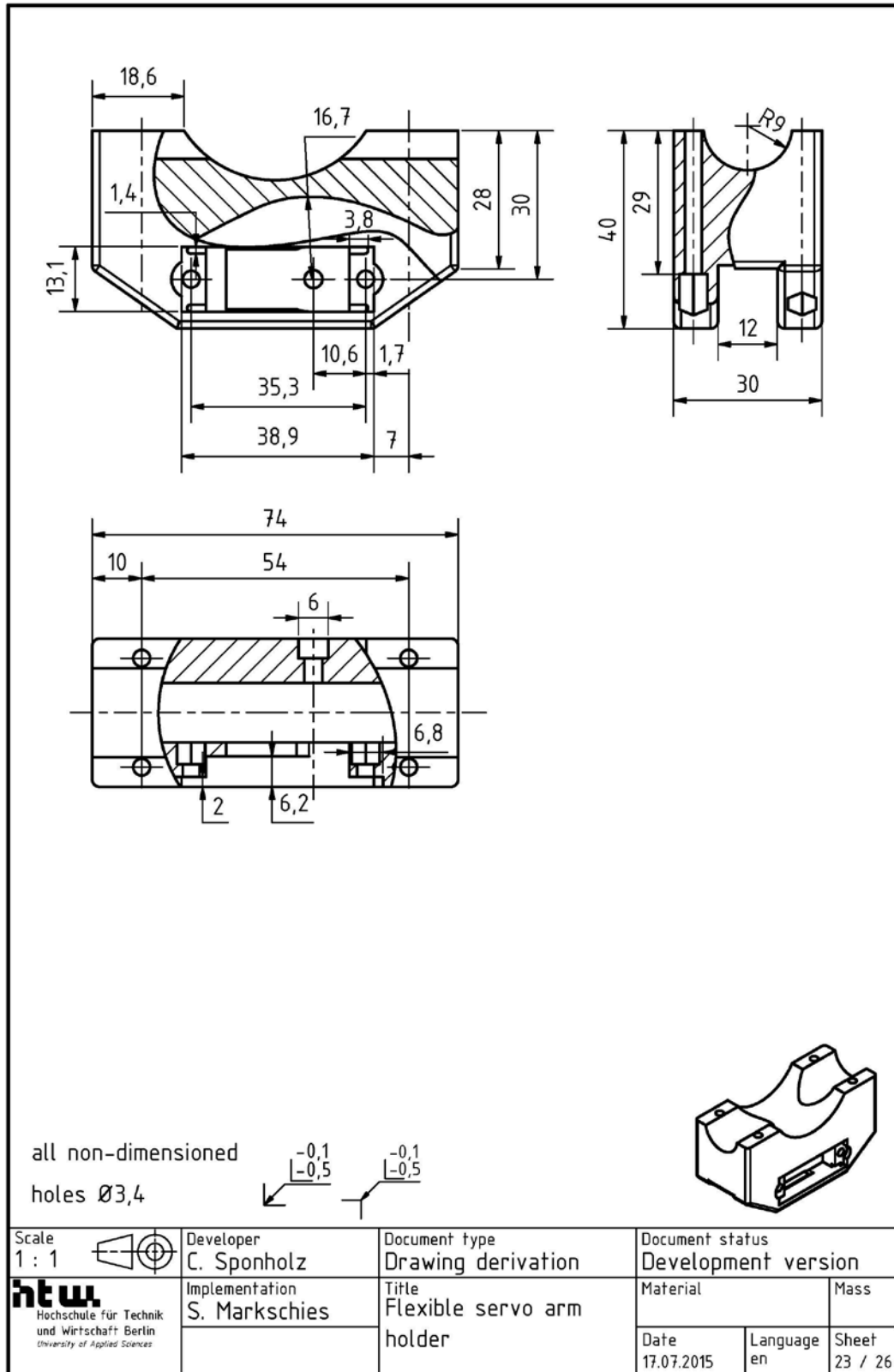


VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

## Annex XXI Drawing derivation of the servo holder of the flexible servo arm

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

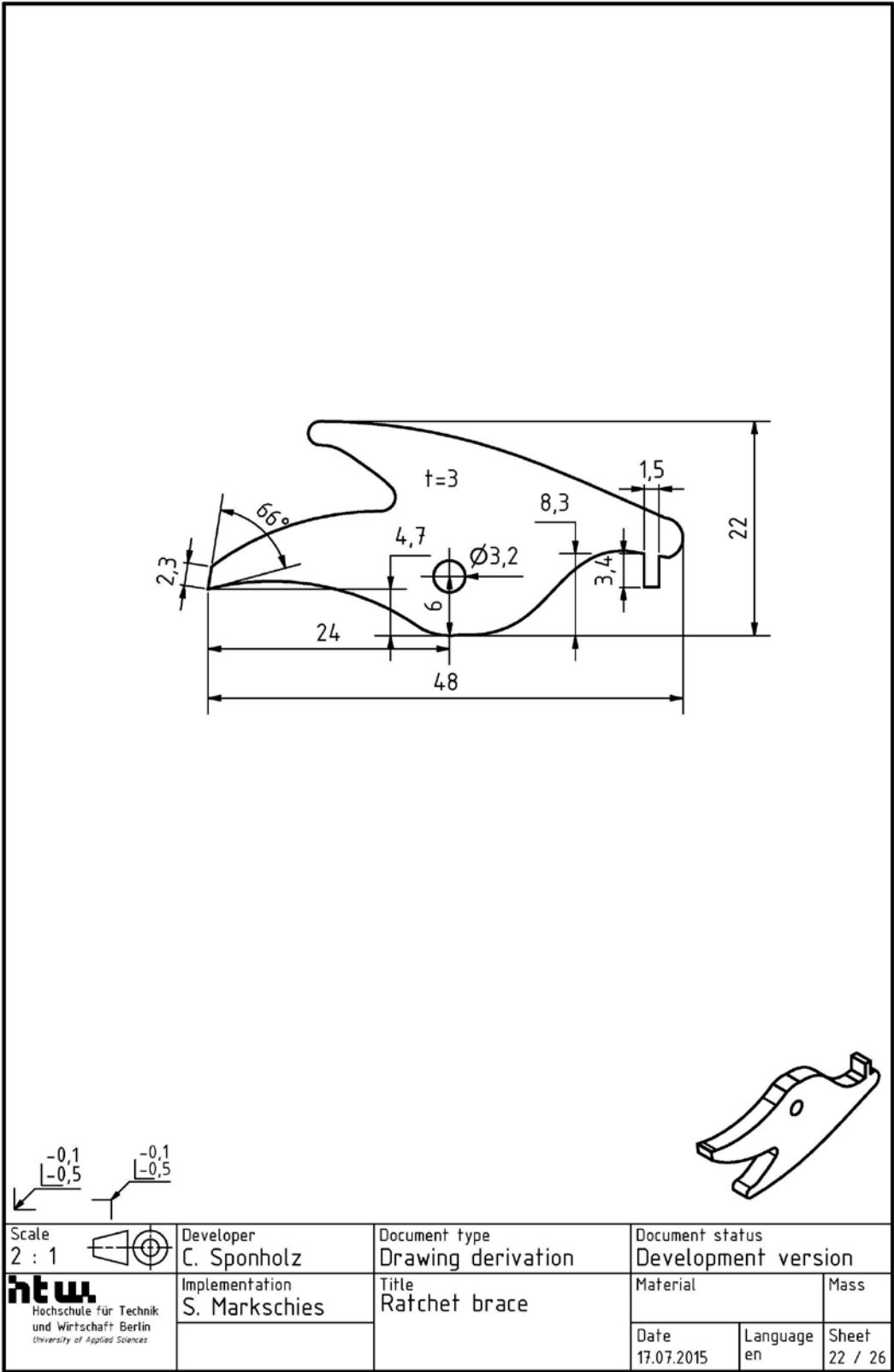
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex XXII    Drawing derivation of the pawl of the ratchet mechanism of the flexible servo arm

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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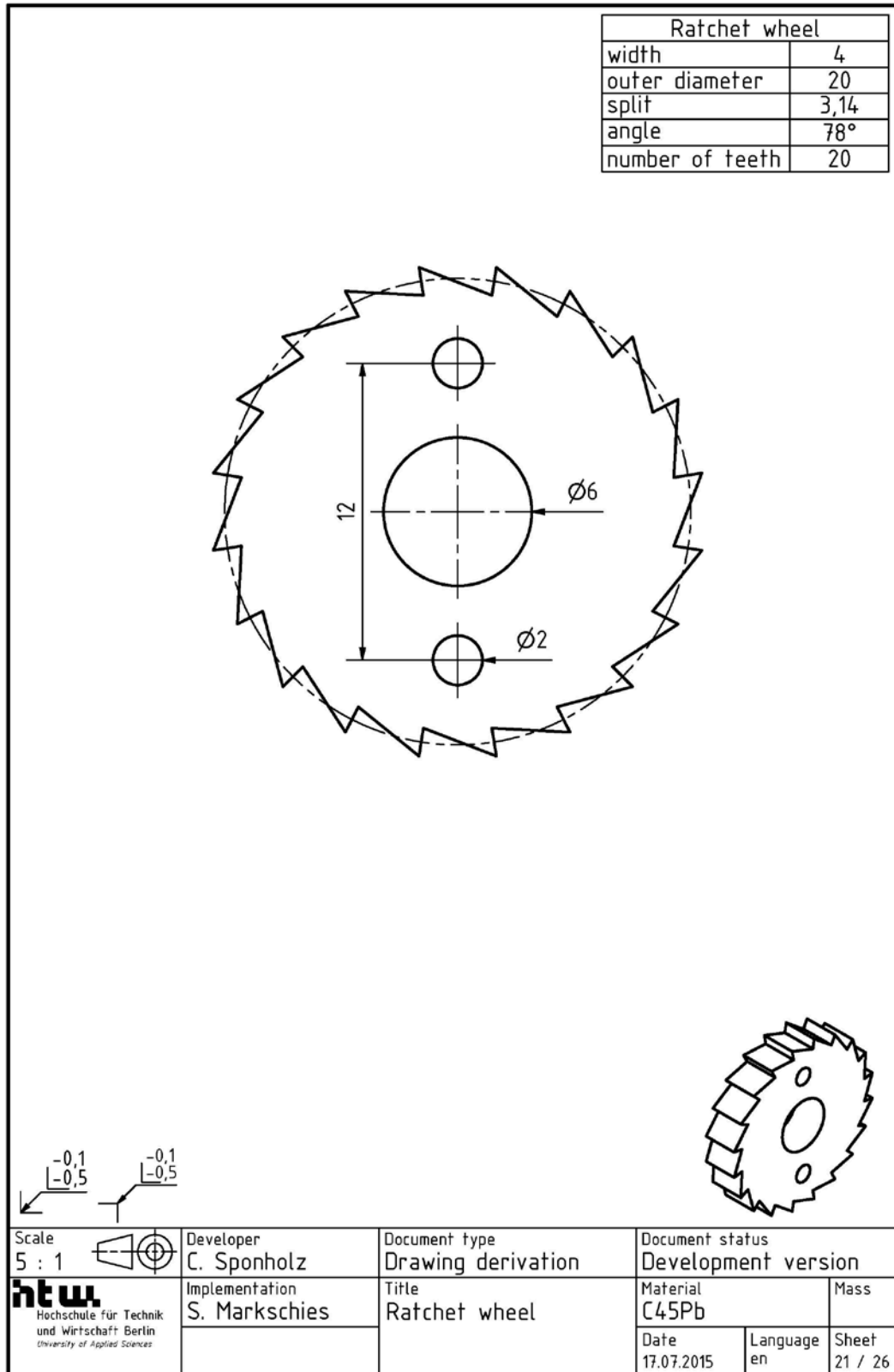
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VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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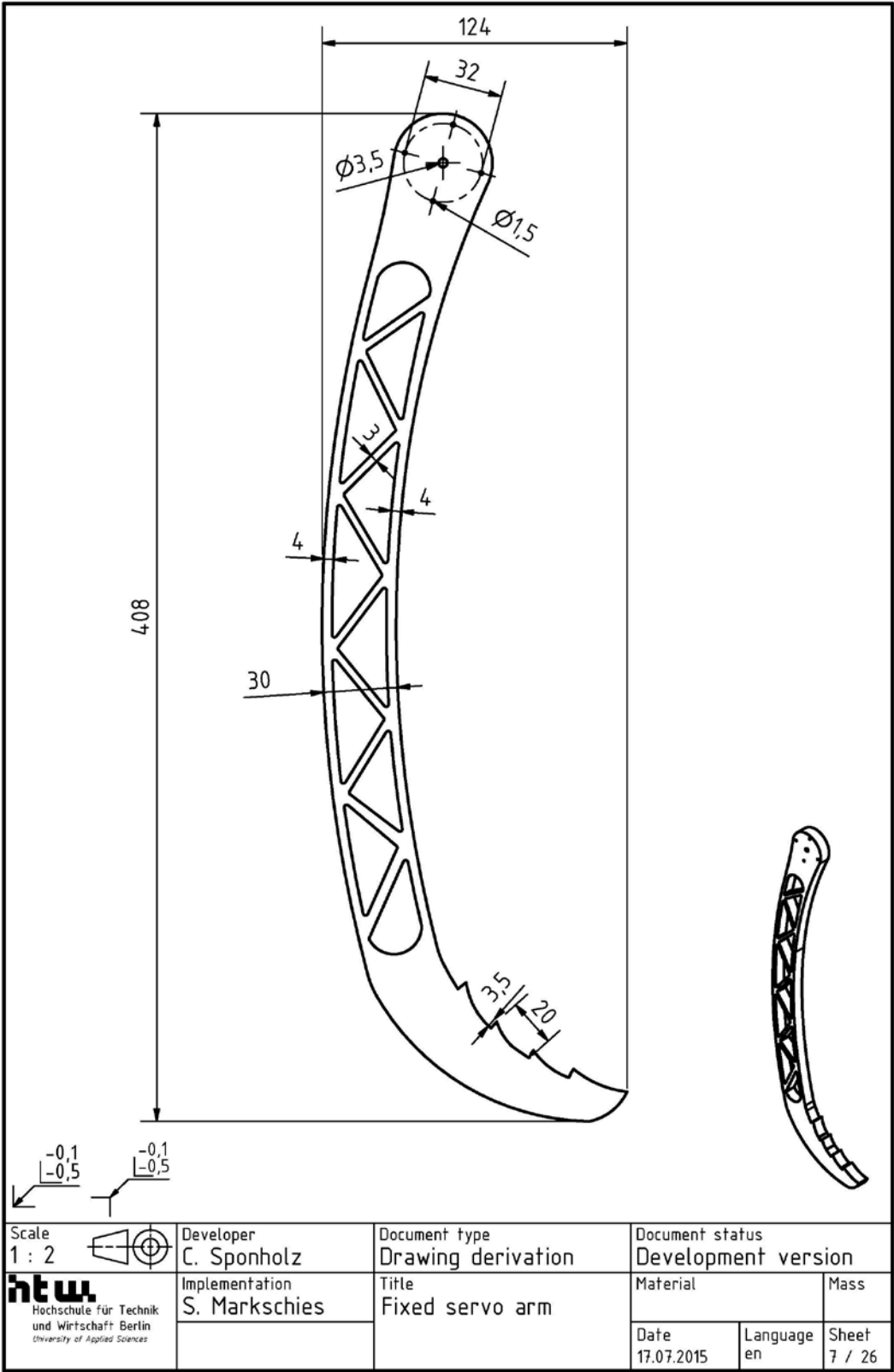


VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex XXIV Drawing derivation of fixed servo arm

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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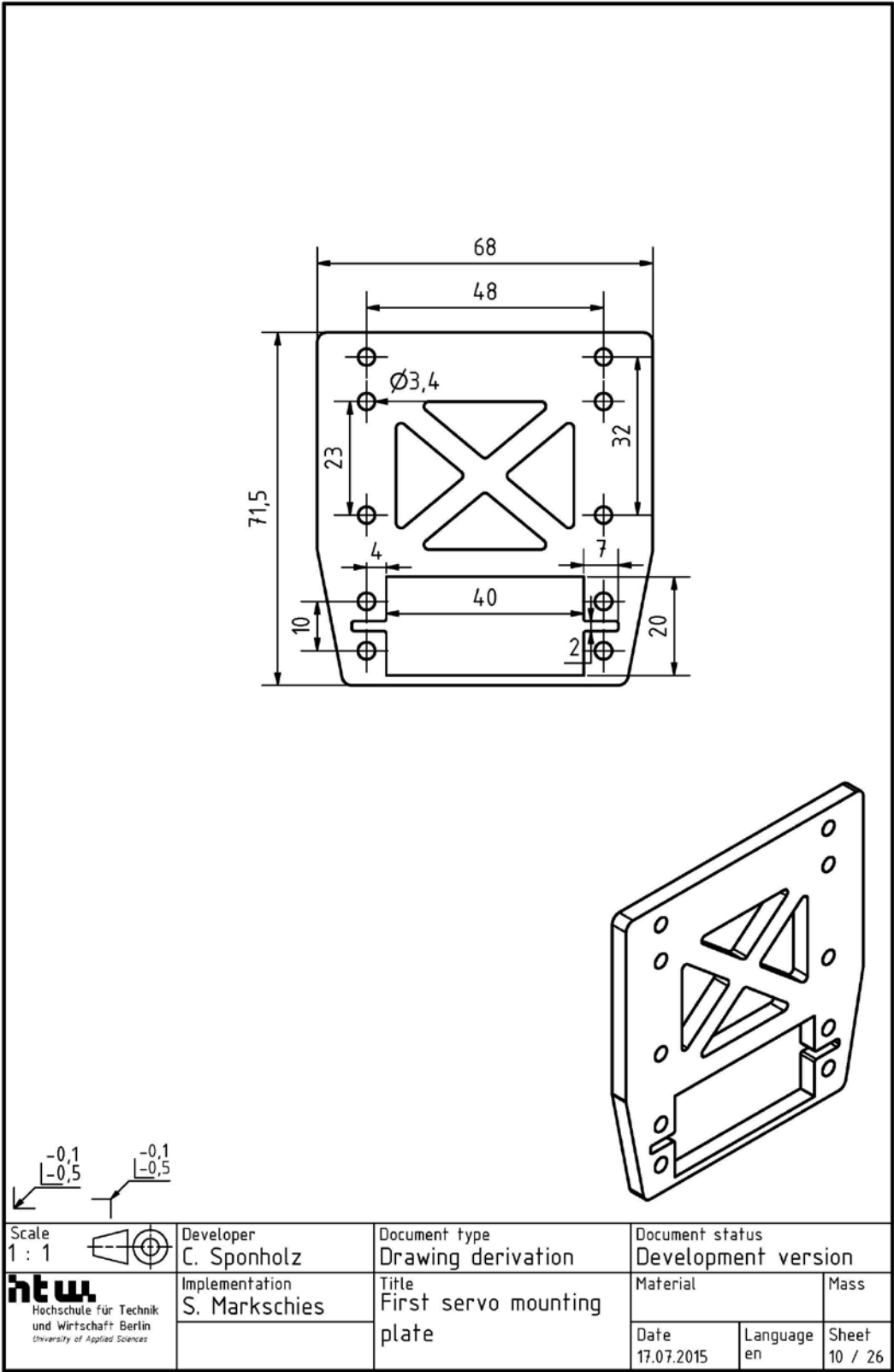
VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex XXV    Drawing derivation of first servo mounting plate

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

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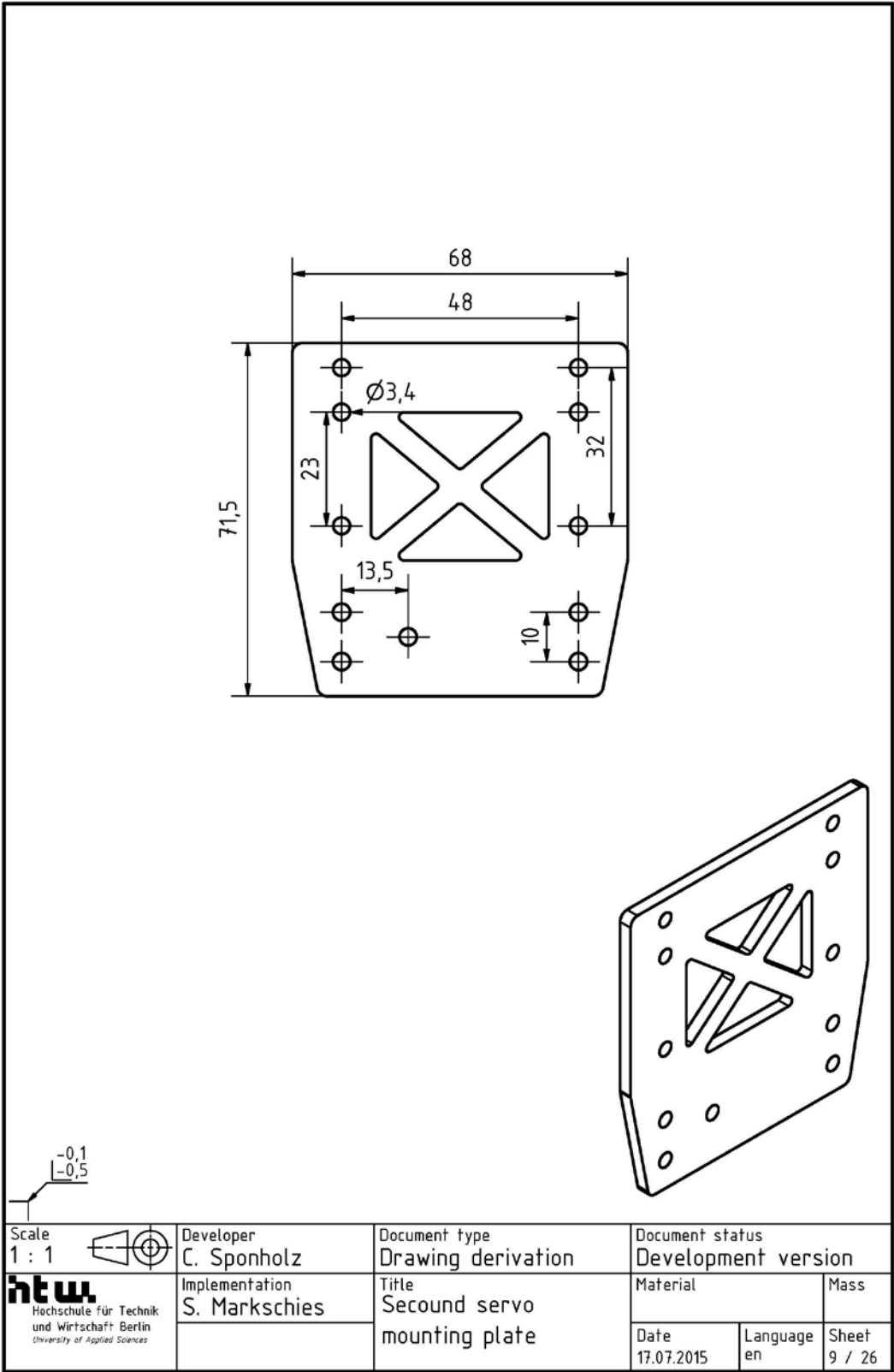
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Annex XXVI Drawing derivation of second servo mounting plate

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

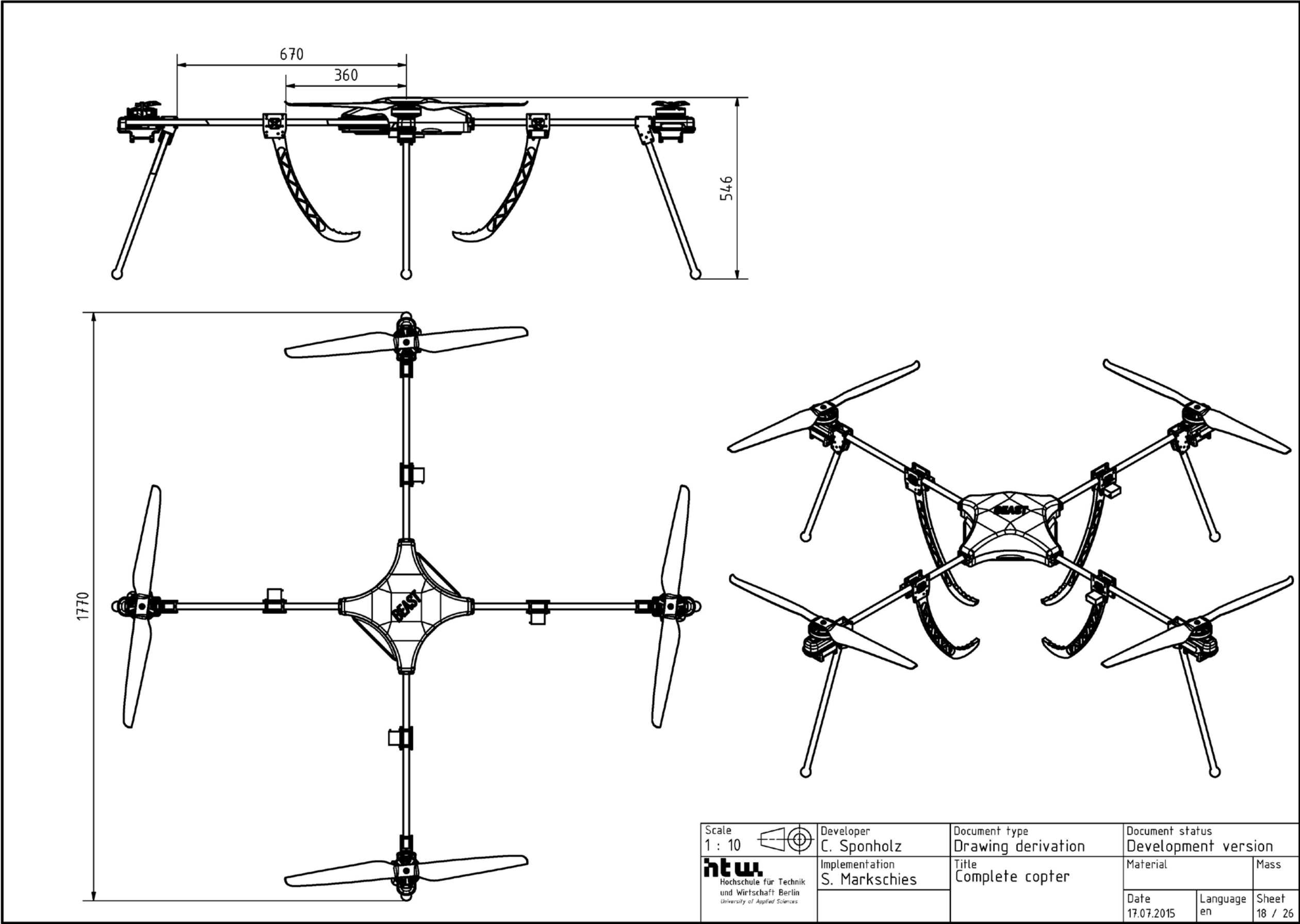
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VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

Annex XXVII Drawing derivation of the whole quad copter

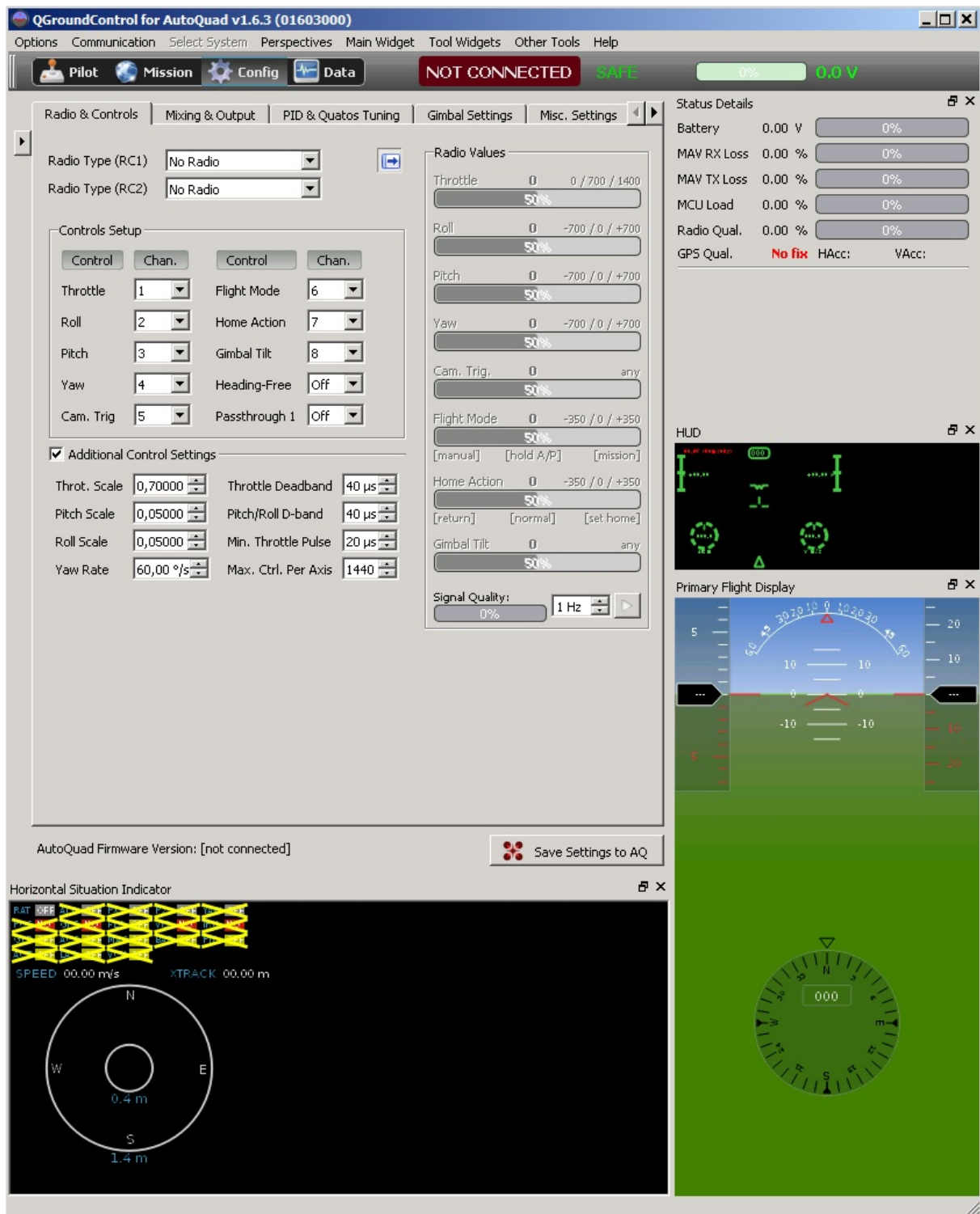


VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT

VON EINEM AUTODESK-SCHULUNGSPRODUKT ERSTELLT



## Annex XXVIII Screenshot of the QGroundControl for AutoQuad (own representation)



## Annex XXIX Motor performance data while ESC calibration

RPM	VOLTS	AMPS
146	0.93	0.04
222	1.42	0.04
294	1.86	0.08
369	2.33	0.14
445	2.80	0.18
516	3.26	0.27
541	3.47	0.37
646	4.19	0.47
724	4.65	0.63
783	5.12	0.74
827	5.58	0.83
919	6.04	1.07
980	6.50	1.32
1029	6.96	1.49
1075	7.42	1.68
1119	7.88	1.91
1167	8.33	2.07
1273	8.78	2.64
1273	8.78	2.64
1380	9.68	3.24
1428	10.13	3.54
1476	10.58	3.83
1519	11.02	4.30
1559	11.47	4.67
1565	11.62	4.98
1632	12.39	5.43
1674	12.83	5.71
1713	13.25	6.25

<b>1736</b>	13.72	6.40
<b>1772</b>	14.13	6.92
<b>1818</b>	14.59	7.39
<b>1846</b>	15.02	7.95
<b>1909</b>	15.43	8.81
<b>1910</b>	15.85	8.66
<b>1992</b>	16.25	9.82
<b>2076</b>	16.66	10.89
<b>2114</b>	17.09	11.65
<b>2122</b>	17.58	12.01
<b>2122</b>	17.97	12.00
<b>2122</b>	18.40	11.87
<b>2215</b>	18.77	13.87
<b>2268</b>	19.17	14.79
<b>2294</b>	19.49	15.86
<b>2294</b>	19.49	15.86
<b>2294</b>	19.49	15.86
<b>2364</b>	20.42	17.74

#define DEFAULT\_FF1TERM +1.394663e-06

#define DEFAULT\_FF2TERM +5.351437e-03

## Annex XXX      Used ESC parameters

Parameter name	Value	Unit
STARTUP_MODE	0	
BAUD_RATE	230400	baud
PTERM	0.500	
ITERM	0.00500	
FF1TERM	+1.38595e-06	
FF2TERM	+5.33756e-03	
MIN_PERIOD	50	us
MAX_PERIOD	12000	us
ADVANCE	15.00	Degs
START_VOLTAGE	1.5	Volts
GOOD_DETECTS_START	48	
BAD_DETECTS_DISARM	32	
MAX_CURRENT	20.00	Amps
START_CURRENT	0.50	Amps
SWITCH_FREQ	20.0	KHz
MOTOR_POLES	42	
PWM_MIN_PERIOD	2200	us
PWM_MAX_PERIOD	25000	us
PWM_MIN_VALUE	750	us
PWM_LO_VALUE	1000	us
PWM_HI_VALUE	1950	us
PWM_MAX_VALUE	2250	us
PWM_MIN_START	1100	us
PWM_RPM_SCALE	2350	RPM
ACTIVE_FREEWHEEL	1	
THR1TERM	+0.00000e+00	
THR2TERM	+1.00000e+00	
RPM_MEAS_LP	0.750	

<b>SERVO_DUTY</b>	5.0	%
<b>SERVO_P</b>	0.050	
<b>SERVO_D</b>	0.000	
<b>SERVO_MAX_RATE</b>	1000.0	deg/s
<b>SERVO_SCALE</b>	360.0	deg
<b>ESC_ID</b>	1	
<b>DIRECTION</b>	1	
<b>AUDIO_VOLUME</b>	0.0	

Annex XXXI Figure of the built mounting plate of the motor  
(own representation)



Annex XXXII Figure of the built motor holder with every required part installed (own representation)



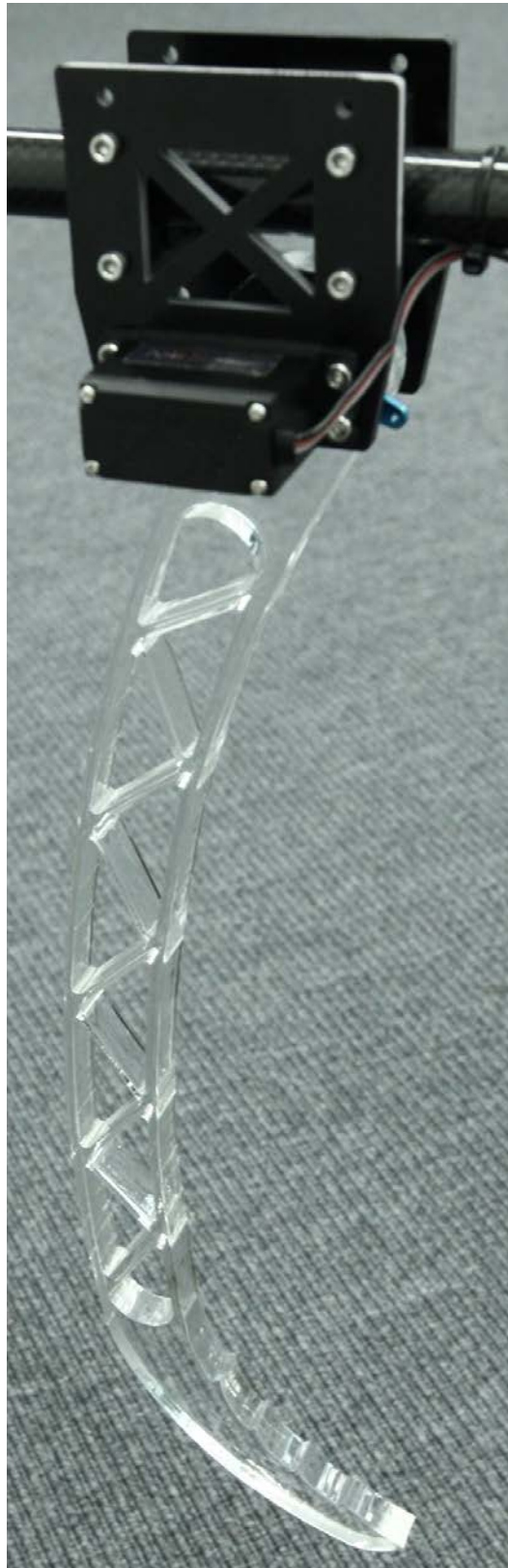


Annex XXXIII Figure of four built arms of the flexible mounting system (own representation)

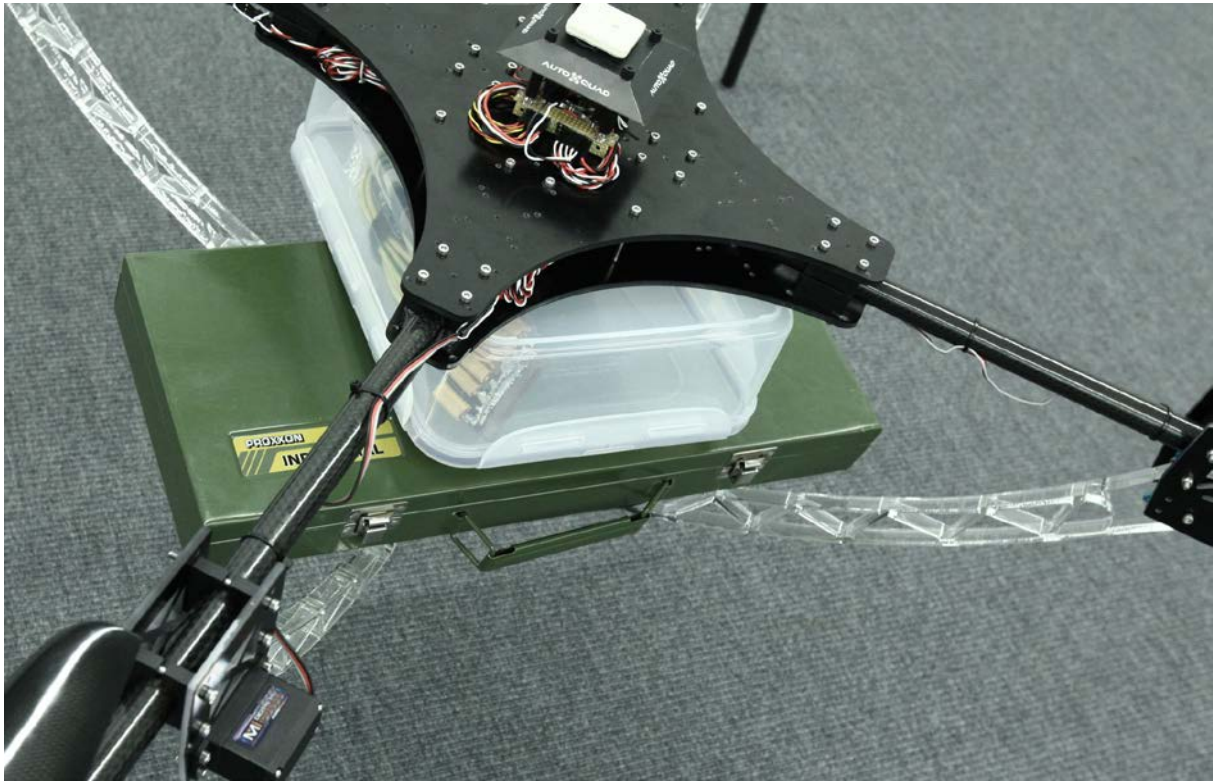




Annex XXXIV Figure of a built and attached arm of the fixed mounting system (own representation)



Annex XXXV Figure of the mounting system with a payload of 5,3 kg (own representation)



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## List of abbreviations

Abbreviation	Meaning
AAV	Autonomous Aerial Vehicle
AIMU	Analog Internal Measurement Unit
BEAST	Better Easy-to-use Aerial Support Transporter
CAN	Controller Area Network
CFRP	Carbon Fibre Reinforced Plastic
CLI	Command Line Interface
DC/DC	DC-to-DC converter (Direct Current/Direct Current)
DFS	Deutsche Flugsicherung
DIMU	Digital Internal Measurement Unit
DJI	Dajiang Innovation Technology Inc.
WxHxD	Width x High x Deep
EEPROM	Electrically Erasable Programmable Read-Only Memory
ESC	Electronic Speed Controller
Et al.	Et alia (and others)
EUR	Euro
FC	Flight Controller
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
GRP	Glass-fibre Reinforced Plastic
HUD	Head-Up Display
IMU	Internal Measurement Unit
Incl.	Inclusive
LiPo	Lithium-ion Polymer Accumulator
MCU	Microcontroller Unit
OS	Operation System
PCB	Printed Circuit Board
PDF	Portable Document Format
PID	Proportional, Integral, and Derivative controller

<b>PONR</b>	Point of No Return
<b>PWM</b>	Pulse-Width Modulation
<b>QGC</b>	QGroundControl
<b>RC</b>	Remote Control
<b>RECOM</b>	DC/DC converter of the RECOM Power GmbH
<b>RPM</b>	Revolutions Per Minute
<b>RTF</b>	Ready to Fly
<b>RTL</b>	Return to Launch
<b>Sqrt</b>	Square root
<b>THW</b>	Bundesanstalt Technisches Hilfswerk
<b>TOW</b>	Take Off Weight
<b>UART</b>	Universal Asynchronous Receiver Transmitter
<b>UAV</b>	Unmanned Aerial Vehicle
<b>UBEC</b>	Ultimate Battery Eliminator Circuit
<b>VAT</b>	Value Added Tax

## List of units

Unit	Meaning
<b>A</b>	Ampere
<b>Ah</b>	Ampere-hour
<b>bps</b>	bits per second
<b>g</b>	gram
<b>kg</b>	kilogram
<b>km</b>	kilometre
<b>km/h</b>	kilometres per hour
<b>m</b>	metre
<b>mA</b>	milliampere
<b>mm</b>	millimetre
<b>N</b>	Newton
<b>Ncm</b>	Newton centimetre
<b>t</b>	tonnes
<b>V</b>	Volt

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## References

- [1] A. Griefß, "Infografik: Drohnen werden zunehmend für zivile Zwecke gebaut | Statista," 06 06 2014. [Online]. Available: [https://d28wbuch0jlv7v.cloudfront.net/images/infografik/normal/infografik\\_2336\\_Bekannte\\_aktive\\_Drohntypen\\_laut\\_RPAS\\_Jahrbuch\\_nach\\_Art\\_der\\_Nutzung\\_n.jpg](https://d28wbuch0jlv7v.cloudfront.net/images/infografik/normal/infografik_2336_Bekannte_aktive_Drohntypen_laut_RPAS_Jahrbuch_nach_Art_der_Nutzung_n.jpg). [Accessed 28 05 2015].
- [2] Thomson Reuters World Wide Web, "WEB OF SCIENCE - Citation Report: 2.031," 02 06 2015. [Online]. Available: [http://apps.webofknowledge.com/CitationReport.do?action=completePIFullGraph&qid=5&SID=P2yhj4SgMYiqzqNHatC&product=UA&search\\_mode=fullPIGraph&cacheurl=no](http://apps.webofknowledge.com/CitationReport.do?action=completePIFullGraph&qid=5&SID=P2yhj4SgMYiqzqNHatC&product=UA&search_mode=fullPIGraph&cacheurl=no). [Accessed 02 06 2015].
- [3] D. Erdos, A. Erdos and S. E. Watkins, "An experimental UAV system for search and rescue challenge," *Aerospace and Electronic Systems Magazine, IEEE*, pp. 32-37, 05 2013.
- [4] M. D'Souza, A. Postula and K. Bialkowski, "COTS Embedded Internet Platform and Blimp UAV for Educational Purposes," 2013. [Online]. Available: <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6723975&tag=1>. [Accessed 02 06 2015].
- [5] S. Hauert, S. Leven, M. Verga, F. Ruini, A. Cangelosi, J.-C. Zufferey and D. Floreano, "Reynolds flocking in reality with fixed-wing robots: communication range vs. maximum turning rate," *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 25-30, 2011.
- [6] A. Kushleyev, D. Mellinger and V. Kumar, "Towards a Swarm of Nano Quadrotors," *Robotics: Science and Systems*, 2012.

- [7] N. Franceschini, F. Ruffier and J. Serres, "Optical Flow Based Autopilots: Speed Control and Obstacle Avoidance," in *Flying Insects and Robots*, Berlin Heidelberg, Springer-Verlag, 2009, pp. 29-50.
- [8] Bundesministerium der Justiz und für Verbraucherschutz, "LuftVO - Einzelnorm," juris GmbH, [Online]. Available: [http://www.gesetze-im-internet.de/luftvo/\\_\\_16.html](http://www.gesetze-im-internet.de/luftvo/__16.html). [Accessed 20 06 2015].
- [9] Bundesministerium der Justiz und für Verbraucherschutz, "LuftVO - Einzelnorm," juris GmbH, [Online]. Available: [http://www.gesetze-im-internet.de/luftvo/\\_\\_22.html](http://www.gesetze-im-internet.de/luftvo/__22.html). [Accessed 03 07 2015].
- [10] T. G. e. a. Piotr Demski, "Automatic Targeting Sentry Turret for Distributed Systems," in *Vision Based Systems for UAV Applications*, Switzerland, Springer, 2013, pp. 47-55.
- [11] J. Wendel, "Anwendungsbeispiel unbemanntes Fluggerät," in *Integrierte Navigationssysteme - Sensordatenfusion, GPS und Inertiale Navigation*, München, Oldengourg Wissenschaftsverlag GmbH, 2007, pp. 281-308.
- [12] Da-Jiang Innovations Science and Technology Co., Ltd., "About DJI Innovations," 03 April 2015. [Online]. Available: [www.dji.com/company](http://www.dji.com/company).
- [13] Da-Jiang Innovations Science and Technology Co., Ltd., "Spreading Wings S1000+ - Features," 03 April 2015. [Online]. Available: <http://www.dji.com/product/spreading-wings-s1000-plus/feature>.
- [14] MICRODRONES GMBH, "microdrones - Testflug für DHL," 04 April 2015. [Online]. Available: <http://www.microdrones.com/de/news/detail/microdrones-im-testflug-fuer-dhl/>.
- [15] microdrones GmbH, "microdrones - md4-1000: longer flight time, more payload and weather resistant - the robust UAV workhorse," 10 April 2015.

- [Online]. Available: <http://www.microdrones.com/en/products/md4-1000/at-a-glance/>.
- [16] Verlag Der Tagesspiegel GmbH, "Drohnen in Europa: Bambi retten, Flüchtlinge jagen," 16 Juli 2013. [Online]. Available: <http://www.tagesspiegel.de/politik/drohnen-in-europa-bambi-retten-fluechtlinge-jagen/8492912.html>. [Accessed 04 April 2015].
- [17] microdrones GmbH, "microdrones - md4-1000 Accessories: proven UAV Solutions for Mapping / GIS, Inspection and Aerial Photography or Video Recordings," 17 März 2015. [Online]. Available: <http://www.microdrones.com/en/products/md4-1000/equipment/>. [Accessed 4 April 2015].
- [18] Schiebel Corporation, "System - Schiebel," Schiebel Corporation, 2015. [Online]. Available: <https://www.schiebel.net/Products/Unmanned-Air-Systems/CAMCOPTER-S-100/System.aspx>. [Accessed 29 04 2015].
- [19] M. Rosenkranz, "airpower.at," Österreich's virtuelles Militärluftfahrt-Journal, 28 06 2005. [Online]. Available: [http://www.airpower.at/news05/0628\\_schiebel-camcopter/](http://www.airpower.at/news05/0628_schiebel-camcopter/). [Accessed 29 04 2015].
- [20] J. Canning and G. Dabringer, "Ethical Challenges of unmanned Systems," in *Ethical and Legal Aspects of unmanned Systems*, Wien, Republik Österreich - Bundesminister für Landesverteidigung und Sport, 2010, pp. 7-19.
- [21] DFS Deutsche Flugsicherung GmbH, "Drohnen gefährden den Flugverkehr," 26 05 2015. [Online]. Available: [https://www.dfs.de/dfs\\_homepage/de/Presse/Pressemitteilungen/2015/26.05.2015.-%20Drohnen%20gefährden%20den%20Flugverkehr/](https://www.dfs.de/dfs_homepage/de/Presse/Pressemitteilungen/2015/26.05.2015.-%20Drohnen%20gefährden%20den%20Flugverkehr/). [Accessed 20 06 2015].

- [22] Bundesministerium der Justiz und für Verbraucherschutz, "LuftVG - Einzelnorm," juris GmbH, [Online]. Available: [http://www.gesetze-im-internet.de/luftvg/\\_\\_33.html](http://www.gesetze-im-internet.de/luftvg/__33.html). [Accessed 20 06 2015].
- [23] Bundesministerium der Justiz und für Verbraucherschutz, "LuftVG - Einzelnorm," juris GmbH, [Online]. Available: [http://www.gesetze-im-internet.de/luftvg/\\_\\_37.html](http://www.gesetze-im-internet.de/luftvg/__37.html). [Accessed 20 06 2015].
- [24] Deutsche Flugsicherung, "Nachrichten für Luftfahrer," 13 03 2008. [Online]. Available: [http://www.rc-network.de/magazin/artikel\\_02/art\\_02-0001/NfL\\_I\\_76-08.pdf](http://www.rc-network.de/magazin/artikel_02/art_02-0001/NfL_I_76-08.pdf). [Accessed 20 06 2015].
- [25] Humboldt-Gymnasium Vaterstetten, "Modellfliegen," Christoph Bergler, 2013. [Online]. Available: <http://www.gym-vaterstetten.de/faecher/fliegen/Modellbau/Modellbau.htm>. [Accessed 05 07 2015].
- [26] Aircraft Owners and Pilots Association, "AOPA Hover Power > 2013 > June," 30 06 2013. [Online]. Available: <http://blog.aopa.org/helicopter/?m=201306>. [Accessed 06 07 2015].
- [27] Dronecode Project, Inc., a Linux Foundation Collaborative Project., "Vibration Damping | Copter," Dronecode Project, Inc., a Linux Foundation Collaborative Project., 2015. [Online]. Available: <http://copter.ardupilot.com/wiki/initial-setup/assembly-instructions/vibration-damping/>. [Accessed 06 07 2015].
- [28] Y. Gao, "What Makes The Quadcopter Design So Great For Small Drones? - Forbes," Forbes.com LLC, 23 12 2013. [Online]. Available: <http://www.forbes.com/sites/quora/2013/12/23/what-makes-the-quadcopter-design-so-great-for-small-drones/>. [Accessed 06 07 2015].
- [29] M. Heiko, "Quadrocopter," 13 02 2013. [Online]. Available: <http://fpv-community.de/wiki/index.php?title=Quadrocopter>. [Accessed 06 07 2015].

- [30] Gyrodyne Helicopter Historical Foundation, "Coaxial Benefits," Gyrodyne Helicopter Historical Foundation, 2013. [Online]. Available: [http://www.gyrodynhelicopters.com/coaxial\\_benefits.htm](http://www.gyrodynhelicopters.com/coaxial_benefits.htm). [Accessed 06 07 2015].
- [31] Robot Kingdom, "Best Flight Controller For Quadcopter and Multicopter - Robot Kingdom," Robot Kingdom, 11 08 2013. [Online]. Available: <http://robot-kingdom.com/best-flight-controller-for-quadcopter-and-multicopter/>. [Accessed 06 07 2015].
- [32] Dajiang Innovation Technology Inc., "WOOKONG-H - Features | DJI," Dajiang Innovation Technology Inc., 2015. [Online]. Available: <http://www.dji.com/product/wookong-h/feature>. [Accessed 06 07 2015].
- [33] Dronecode Project, Inc., a Linux Foundation Collaborative Project, "Pixhawk Autopilot - PX\$ Autopilot Project," Dronecode Project, Inc., a Linux Foundation Collaborative Project., [Online]. Available: <https://pixhawk.org/modules/pixhawk>. [Accessed 06 07 2015].
- [34] AutoQuad, "AutoQuad 6 | AutoQuad," AutoQuad, [Online]. Available: <http://autoquad.org/about/>. [Accessed 05 07 2015].
- [35] AutoQuad, "AutoQuad6 Full-Size Flight Controller," AutoQuad, 16 11 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/autoquad-hardware-connections/>. [Accessed 13 07 2015].
- [36] AutoQuad, "The AutoQuad ESC32 – a yet unseen electronic speed controller," AutoQuad, [Online]. Available: <http://autoquad.org/esc32/>. [Accessed 05 07 2015].
- [37] AutoQuad, "ESC32 Hardware Setup | AutoQuad," AutoQuad, 18 06 2012. [Online]. Available: <http://autoquad.org/wiki/wiki/esc32/esc32-hardware-setup/>. [Accessed 06 07 2015].

- [38] T-motor, "AIR 40A - ESC - T-MOTOR," T-motor, 2013. [Online]. Available: [http://www.rctigermotor.com/html/2014/esc\\_1223/285.html](http://www.rctigermotor.com/html/2014/esc_1223/285.html). [Accessed 06 07 2015].
- [39] Plettenberg Elektromotoren GmbH & Co. KG, "Terminator 30 Evo," Plettenberg Elektromotoren GmbH & Co. KG, 2013. [Online]. Available: <http://plettenberg-motoren.net/index.php/de/plettenberg-motoren/plettenberg-brushless-motoren/terminatorevo/terminator-30-evo>. [Accessed 05 07 2015].
- [40] Plettenberg Elektromotoren GmbH & Co. KG, "Copter 30," Plettenberg Elektromotoren GmbH & Co. KG, 2013. [Online]. Available: <http://plettenberg-motoren.net/index.php/de/plettenberg-motoren/plettenberg-brushless-motoren/copter/copter-30>. [Accessed 05 07 2015].
- [41] Plettenberg Elektromotoren GmbH & Co. KG, "Xtra 25 Evo.," Plettenberg Elektromotoren GmbH & Co. KG, 2013. [Online]. Available: <http://plettenberg-motoren.net/index.php/de/plettenberg-motoren/plettenberg-brushless-motoren/xtra-evo/xtra-25-evo>. [Accessed 05 07 2015].
- [42] T-motor, "U8 Pro - Efficiency Type - T-MOTOR," T-motor, 2013. [Online]. Available: [http://www.rctigermotor.com/html/2013/Efficiency-Type\\_1219/176.html](http://www.rctigermotor.com/html/2013/Efficiency-Type_1219/176.html). [Accessed 07 05 2015].
- [43] T-motor, "29x9.5prop - Carbon Fibre Prop - T-MOTOR," T-motor, 2013. [Online]. Available: [http://www.rctigermotor.com/html/2013/prop\\_0805/13.html](http://www.rctigermotor.com/html/2013/prop_0805/13.html). [Accessed 05 07 2015].
- [44] RECOM Electronic GmbH & Co. KG., "recom-international.com," 2015. [Online]. Available: [http://www.recom-international.com/pdf/Innoline/R-78Bxx-1.5\\_L.pdf](http://www.recom-international.com/pdf/Innoline/R-78Bxx-1.5_L.pdf). [Accessed 05 07 2015].

- [45] RECOM Electronic GmbH & Co. KG., "recom-international.com," 2015. [Online]. Available: [http://www.recom-international.com/pdf/Innoline/R-78Bxx-1.0\\_L.pdf](http://www.recom-international.com/pdf/Innoline/R-78Bxx-1.0_L.pdf). [Accessed 05 07 2015].
- [46] T-motor, "FLAME 80A - ESC - T-MOTOR," T-motor, 2013. [Online]. Available: [http://www.rctigermotor.com/html/2014/esc\\_1215/281.html](http://www.rctigermotor.com/html/2014/esc_1215/281.html). [Accessed 06 07 2015].
- [47] S. Angermann and A. Frahm, Auslegung und Konstruktion einer 4-rotorigen, schwebenden Messplattform für Nutzlastanforderungen von bis zu 10kg., Wildau: TH-Wildau, 2009.
- [48] Genspow GmbH, "Tattu 22000mAh 22.2V 25C 6S1P Lipo Battery Pack - Gens Ace," Genspow GmbH, 2013. [Online]. Available: <http://www.gensace.de/recommend-products/tattu-22000mah-22-2v-25c-6s1p-lipo-battery-pack.html>. [Accessed 07 05 2015].
- [49] SLS - StefansLipoShop GmbH, "SLS APL 21000mAh 6S1P 22,2V 15C+/30C - Lipo Modellbau Akkus bei Stefansliposhop online kaufen," SLS - StefansLipoShop GmbH, 2012. [Online]. Available: <http://www.stefansliposhop.de/liposhop/SLS-Multirotor/hohe-Kapazitaeten/SLS-APL-21000mAh-6S1P-22-2V-15C-30C::1403.html>. [Accessed 07 05 2015].
- [50] WORLD-OF-HELI, "PULSE LIPO 16000mAh 6S1P 22.2V 15C - WORLD-OF-HELI," WORLD-OF-HELI, 2015. [Online]. Available: <http://www.world-of-heli.de/akkus-lipos/pulse/grosse-kapazitaeten/pulse-lipo-16000mah-6s1p-22.2v-15c.html>. [Accessed 07 05 2015].
- [51] P. Bake, "FCP HL - 18mm - XL - universal Centerplate - Set für Quadrocopter," Paul Bake, 2011. [Online]. Available: [http://flyduino.net/Multikopter-Rahmen\\_1](http://flyduino.net/Multikopter-Rahmen_1). [Accessed 26 05 2015].



- [52] A. Fernandez, "Basic structural dynamics in multicopters," 03 2014. [Online]. Available: <http://autoquad.org/wp-content/plugins/download-monitor/download.php?id=127>. [Accessed 28 05 2015].
- [53] M. S. Agerer, "Spannungs-Dehnungs-Diagramm," Markus Sebastian Agerer, [Online]. Available: <http://www.maschinenbau-wissen.de/skript3/werkstofftechnik/metall/25-spannungs-dehnungs-diagramm>. [Accessed 31 05 2015].
- [54] O. Kipf, "Wissen über CFK," 07 2008. [Online]. Available: [http://www.cg-tec.de/uploads/media/Wissen\\_\\_ber\\_CFK\\_Modul\\_2\\_08.pdf](http://www.cg-tec.de/uploads/media/Wissen__ber_CFK_Modul_2_08.pdf). [Accessed 31 05 2015].
- [55] The Engineering ToolBox, "Tensile Modulus - Modulus of Elasticity or Young's Modulus - for some common Materials," The Engineering ToolBox, [Online]. Available: [http://www.engineeringtoolbox.com/young-modulus-d\\_417.html](http://www.engineeringtoolbox.com/young-modulus-d_417.html). [Accessed 31 05 2015].
- [56] Propex Operating Company, LLC, "Technical Analysis - Curv - Propex Fabrics," Propex Operating Company, LLC, 2007. [Online]. Available: <http://curvonline.com/deutsch/products/analysis.html>. [Accessed 01 06 2015].
- [57] HOBBY KING TECHNOLOGY LTD, "N/A," 2015. [Online]. Available: <http://cdn.hobbyking.com/hobbyking/store/images/servoDiag.gif>. [Accessed 24 05 2015].
- [58] Blue Bird Technology Co., Ltd., "RC Servos in Taiwan," Blue Bird Technology Co., Ltd., 2015. [Online]. Available: <http://www.blue-bird-model.com/en/servos/bms-390dmh.html>. [Accessed 24 05 2015].
- [59] DONG YANG MODEL TECHNOLOGY CO., LIMITED, "DONG YANG MODEL TECHNOLOGY CO., LIMITED | Servo | Brushless motor | Speed controller | Propeller | Multi-Rotor Brushless Motor | Gimbal ...," DONG

- YANG MODEL TECHNOLOGY CO., LIMITED, 2014. [Online]. Available: <http://www.gotekrc.com/ProductShow.asp?ID=38>. [Accessed 24 05 2015].
- [60] Blue Bird Technology Co., Ltd., "RC Servos / HV Servos in Taiwan," Blue Bird Technology Co., Ltd., 2015. [Online]. Available: <http://www.blue-bird-model.com/en/highvoltageservo/bms-2514.html>. [Accessed 24 05 2015].
- [61] HexTronik Limited, "HobbyKing™ Mi Digital High Torque Servo HV/MG 60g/31kg/0.15," HexTronik Limited, [Online]. Available: [http://www.hobbyking.com/hobbyking/store/\\_\\_27749\\_\\_HobbyKing\\_8482\\_Mi\\_Digital\\_High\\_Torque\\_Servo\\_HV\\_MG\\_60g\\_31kg\\_0\\_15.html](http://www.hobbyking.com/hobbyking/store/__27749__HobbyKing_8482_Mi_Digital_High_Torque_Servo_HV_MG_60g_31kg_0_15.html). [Accessed 12 07 2015].
- [62] AutoQuad, "The CAN-Bus," AutoQuad, 15 12 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/esc32/can-bus/>. [Accessed 13 07 2015].
- [63] AutoQuad, "AQ& Connectors & LEDs," AutoQuad, 17 10 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/autoquad-hardware-connections/flightcontroller-setup/>. [Accessed 13 07 2015].
- [64] S. Tatham, O. Dunn and B. Harris, "PuTTY: A Free Telnet/SSH Client," 19 05 2015. [Online]. Available: <http://www.chiark.greenend.org.uk/~sgtatham/putty/>. [Accessed 14 06 2015].
- [65] AutoQuad, "ESC32 Calibrations | AutoQuad," 06 08 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/esc32/esc32-calibrations/>. [Accessed 21 06 2015].
- [66] A. Schwarz, "UART - Mikrokontroller.net," [Online]. Available: <http://www.mikrocontroller.net/articles/UART>. [Accessed 14 06 2015].
- [67] W. Zeller, "Baud ungleich BPS," Fido-Netz, [Online]. Available: <http://www.handshake.de/infobase/dfue/modem/t243.htm>. [Accessed 14 06 2015].

- [68] AutoQuad, "ESC32 Configuration and Modes | AutoQuad," 19 08 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/esc32/esc32-configuration-and-modes/>. [Accessed 22 06 2015].
- [69] B. Ver..., "copter-gcs," 03 2012. [Online]. Available: <http://code.google.com/p/copter-gcs/>. [Accessed 14 06 2015].
- [70] C. Schmid, "Ground Control Station for Android | AutoQuad," 07 10 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/configuring-autoquad-flightcontroller/autoquad-software-setup/autoquad-ground-control-station-android/>. [Accessed 22 06 2015].
- [71] J. Hermansen, "AutoQuad IMU Calibration," 18 06 2012. [Online]. Available: <http://autoquad.org/wiki/wiki/configuring-autoquad-flightcontroller/autoquad-calibrations/>. [Accessed 29 05 2015].
- [72] J. Hermansen, "Fully Temperature Compensated | AutoQuad," AutoQuad, 18 10 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/configuring-autoquad-flightcontroller/autoquad-calibrations/fully-temperature-compensated-imu/fully-temperature-compensated/>. [Accessed 31 05 2015].
- [73] AutoQuad, "Ground Control Station for PC | AutoQuad," AutoQuad, 12 01 2015. [Online]. Available: <http://autoquad.org/wiki/wiki/configuring-autoquad-flightcontroller/autoquad-software-setup/autoquad-ground-control-station-windows/>. [Accessed 31 05 2015].
- [74] J. Hermansen, "Dynamic Data Gathering - AutoQuad," AutoQuad, 23 08 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/configuring-autoquad-flightcontroller/autoquad-calibrations/fully-temperature-compensated-imu/dynamic-calibration/>. [Accessed 01 06 2015].
- [75] J. Hermansen, Interviewee, *Technical details about the AutoQuad ESC32v3*. [Interview]. 08 06 2015.

- [76] AutoQuad, "AutoQuad M4 - Micro Flight Controller | AutoQuad," AutoQuad, 22 03 2015. [Online]. Available: <http://autoquad.org/wiki/wiki/m4-microcontroller/>. [Accessed 13 07 2015].
- [77] AutoQuad, "AutoQuad IMU Calibration," AutoQuad, 18 10 2014. [Online]. Available: <http://autoquad.org/wiki/wiki/configuring-autoquad-flightcontroller/autoquad-calibrations/>. [Accessed 13 07 2015].
- [78] AutoQuad, "Simple Onboard DIMU Calibration | AutoQuad," AutoQuad, 22 12 2015. [Online]. Available: <http://autoquad.org/wiki/wiki/configuring-autoquad-flightcontroller/autoquad-calibrations/onboard-imu-calibration/>. [Accessed 13 07 2015].
- [79] Henkel Europe, "LOCTITE SI 5926," 05 2014. [Online]. Available: <http://tds.henkel.com/tds5/docs/SI%205926%20BLUE-EN.PDF>. [Accessed 07 06 2015].
- [80] M. Lahr, "Technische Hochschule Wildau - TH Wildau : Equipment & Materialien," TH Wildau, [Online]. Available: <http://www.th-wildau.de/forschungsgruppen/fg-innovation/creativelab/equipment-materialien.html>. [Accessed 05 06 2015].
- [81] cameo Laser Franz Hagemann GmbH, "Epilog Zing 24 | cameo laser - Ihr Partner für CO2-Laser, Faserlaser und YAG-Laser," cameo Laser Franz Hagemann GmbH, [Online]. Available: <https://www.cameo-laser.de/de/systeme/co2-laser/epilog-zing-24/>. [Accessed 05 06 2015].
- [82] Evonik Röhm GmbH, "ACRIFIX - Klebstoffe und Hilfsmittel," [Online]. Available: <http://www.acrylglas-werbeschild-zuschnitt.de/Acrylglaskleber.pdf>. [Accessed 08 06 2015].
- [83] MakerBot Industries, LLC, "MakerBot Replicator 2X," MakerBot Industries, LLC, 2009-2015. [Online]. Available: <http://store.makerbot.com/replicator2x>. [Accessed 05 06 2015].

- [84] Verbund Offener Werkstätten, "Leih-Lasercutter - Verbund Offener Werkstätten," Verbund Offener Werkstätten, 20 02 2015. [Online]. Available: <http://www.offene-werkstaetten.org/wiki/index.php/Leih-Lasercutter>. [Accessed 07 06 2015].
- [85] Evonik Industries AG, "Machining PLEXIGLAS - You meet PLEXIGLAS every day.," Evonik Industries AG , 01 07 2014. [Online]. Available: <http://www.plexiglas.de/product/plexiglas/en/about/faq/Pages/machining.aspx>. [Accessed 07 06 2015].
- [86] Globe Flight GmbH, "DJI Wookong M Multikopter Steuerung mit GPS, 830,00€, FPV-Globe," 04 April 2015. [Online]. Available: <http://www.globe-flight.de/DJI-S1000-Oktokopter-Octocopter-Canon-5D-Mark-III-Black-Magic-Pocket-Cinema>.
- [87] StefansLipoShop GmbH, "SLS APL 21000mAh 6S1P 22,2V 15C+/30C - Lipo Modellbau Akkus bei Stefansliposhop online kaufen," 04 April 2015. [Online]. Available: <http://www.stefansliposhop.de/liposhop/SLS-Multirotor/hohe-Kapazitaeten/SLS-APL-21000mAh-6S1P-22-2V-15C-30C::1403.html>.
- [88] INTERNATIONAL ELECTRONICAL COMMISSION, INTERNATIONAL STANDARD - Degrees of protection provided by enclosures (IP Code), Virginia, 2002.
- [89] RC Reference, "RCReference | | Turnigy - TGY-390V HV Metal gear Coreless Digital Servo w/ Heat Sink," RC Reference, 2013. [Online]. Available: [http://www.rcreference.com/servos/product\(turnigy-tgy-390v-hv-metal-gear-coreless-digital-servo-w-heat-sink\)\\_4271.htm](http://www.rcreference.com/servos/product(turnigy-tgy-390v-hv-metal-gear-coreless-digital-servo-w-heat-sink)_4271.htm). [Accessed 24 05 2015].
- [90] Material 4 Print GmbH & Co. KG, "PLA Filamente kaufen, 3D-Druckmaterial für den 3D-Druck kaufen," Material 4 Print GmbH & Co. KG, 2014. [Online]. Available: [http://www.material4print.de/de/m4p-druckbereich\\_\\_78/](http://www.material4print.de/de/m4p-druckbereich__78/). [Accessed 31 05 2015].

- [91] L. Meier, "Home - QGroundControl GCS," Institute for Visual Computing, Swiss Federal Institute of Technology Zurich, 2010. [Online]. Available: <http://qgroundcontrol.org/>. [Accessed 31 05 2015].
- [92] AutoQuad, "Dynamic Calibration Dance Step by Step - Firstd Sequence," 19 10 2014. [Online]. Available: [http://autoquad.org/wp-content/uploads/2012/07/Calibso-AutoQuad-Dynamic-Calibration\\_seq1.png](http://autoquad.org/wp-content/uploads/2012/07/Calibso-AutoQuad-Dynamic-Calibration_seq1.png). [Accessed 01 06 2015].
- [93] D. AG, "M8Cube - DATRON," DATRON AG, [Online]. Available: [https://www.datron.de/de\\_de/cnc-fraesmaschinen/maschinen/m8cube.html](https://www.datron.de/de_de/cnc-fraesmaschinen/maschinen/m8cube.html). [Accessed 06 06 2015].
- [94] DATRON AG, "DATRON M8Cube," 08 10 2012. [Online]. Available: <http://www.neutech.de/downloads/datron/fraesmaschinen/DATRON-M8Cube-kompakt.pdf>. [Accessed 06 06 2015].
- [95] Alutronic Kühlkörper GmbH Co. KG, "Produkt Datenblatt Typ: WK709/10ml," 28 04 2015. [Online]. Available: <http://alutronic.de/files/downloads/6141.PDF>. [Accessed 07 06 2015].
- [96] Alutronic Kühlkörper GmbH Co. KG, "Wärmeleitkleber WK709," 10 2005. [Online]. Available: [https://cdn-reichelt.de/documents/datenblatt/C800/WK709\\_DATENBLATT.pdf](https://cdn-reichelt.de/documents/datenblatt/C800/WK709_DATENBLATT.pdf). [Accessed 07 06 2015].
- [97] The wiki for and by the whole fab community., "Portal:Equipment - Fab Lab Wiki - by NMÍ Kvikan," NMÍ Kvikan, 16 08 2014. [Online]. Available: <http://wiki.fablab.is/wiki/Portal:Equiment>. [Accessed 07 06 2015].
- [98] Fabulous St.Pauli, "Internationale Fab Charter | Fabulous St.Pauli," Fabulous St.Pauli, 2007. [Online]. Available: <http://www.fablab-hamburg.org/ein-fab-lab-fuer-stpauli/selbstverstandnis/>. [Accessed 07 06 2015].

- [99] AutoQuad, "Quatos Adaptive Attitude Control," 03 03 2015. [Online]. Available: <http://autoquad.org/wiki/wiki/quatos-adaptive-control/>. [Accessed 22 06 2015].
- [100] Drone Controls, "Get License," World Design Group, Inc., 2014. [Online]. Available: <http://www.drone-controls.com/index.cfm/page/get-quatos-license.htm>. [Accessed 22 06 2015].
- [101] Dronecode Project, Inc., a Linux Foundation Collaborative Project, "Traditional Helicopter - Suggested Parts List | Copter," Dronecode Project, Inc., a Linux Foundation Collaborative Project, 2015. [Online]. Available: <http://copter.ardupilot.com/wiki/traditional-helicopters/traditional-heli-parts-list/>. [Accessed 05 07 2015].

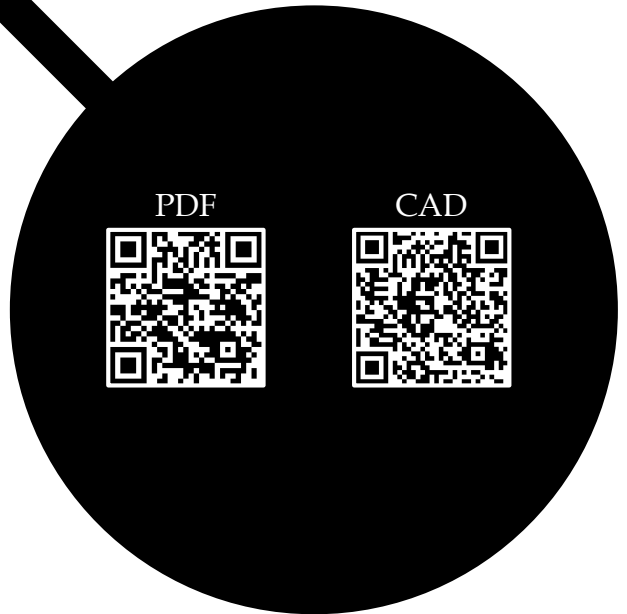
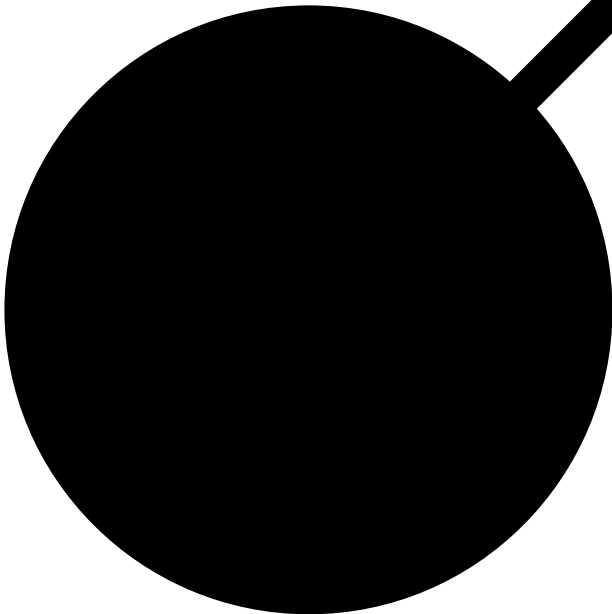
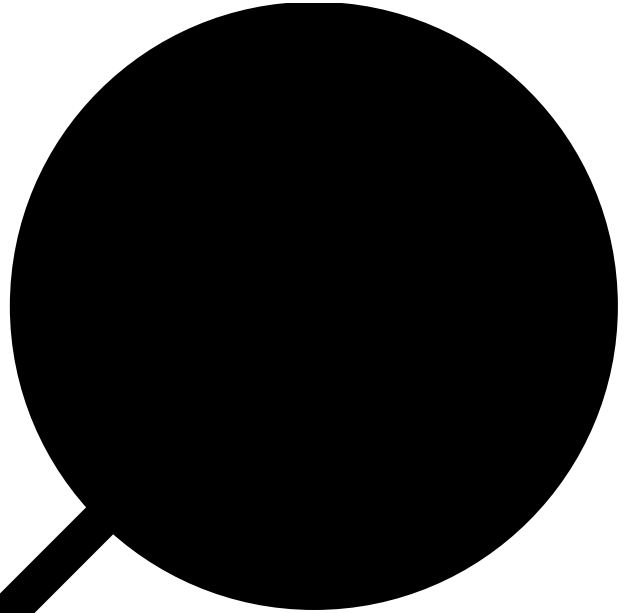
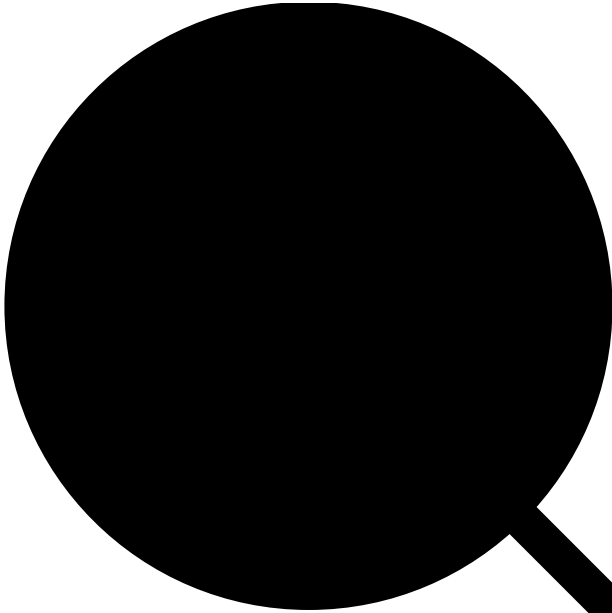
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