ELECTRIC VTOL UAV CONFIGURATION STUDIES AND OPTIMIZATION WITHIN AIRCRAFT DESIGN PRACTICAL COURSE AT TECHNICAL UNIVERSITY OF MUNICH

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Abstract

The aircraft design practical course at Technical University of Munich (TUM) Institute of Aircraft Design (LLS) uses a project-based learning philosophy. The aim of this course is to show the high interdependency of the required different disciplines and the iterative process of aircraft design and finally prepares the students for their later position in industry. To achieve those goals the course is set up as a role play with the students being employees of a fictional design bureau. The task given to the design bureau is assigned from a real aviation company to also enable the students to get insight in the real business. Varying the design topic each run ensures a high motivation of the students. After conceptual studies, the students are divided into 4 divisions (structure, aerodynamics, simulation, propulsion) for detailed design like in industry. Besides the technical knowledge of each discipline, soft skills like communication, presentation, planning and time scheduling are therefore encouraged. The content of the paper describes the concept of the course in more detail as well as the results of an example design task. The task presented is the configuration comparison and optimization of fixed-wing vertical takeoff and landing (VTOL) unmanned aerial vehicles (UAV) designed for the medical express UAV outback challenge 2016.

Nomenclature

VTOL = Vertical Take-Off and Landing
UAV = Unmanned Aerial Vehicle
MTOW = Maximum Take-Off Weight
ESC = Electronic Speed Controller

1 Introduction

The Practical Course Aircraft Design is taught by the Institute of Aircraft Design at Technical University of Munich since 2011. In this practical course the students learn to apply the skills and knowledge gained in other courses like aircraft design, aerodynamics, light weight structures, propulsion systems etc. They perform an iterative aircraft design process and understand the interactions between the various disciplines through working in a simulated industry design team environment. This means that after the conceptual design phase, where every student has to sketch and present his own configuration, the students are grouped in four divisions - simulation, aerodynamic, structure and propulsion system. Within those departments they work together on the selected concepts during the conceptual design phase. This special setup furthermore promotes soft skills abilities like working in a team, communication, presentation, planning and scheduling. At defined milestones the students have to present their work and the course concludes with a final presentation and a written report.

The design task is different each term so up to date topics can be worked on. To further motivate the students and link them to industry, the design task is given to them from a company.

The task of the presented work in this paper was the design of a fixed-wing VTOL UAV for the medical express UAV outback challenge 2016.

There are also many other scenarios where the advantage of fixed-wing VTOL without needing any infrastructure and easy operation on the one hand and considerably improved endurance and speed compared to multicopters on the other hand are favorable or even mandatory. Thus there are many UAV companies that are looking into the development of VTOL UAV. One of them is Quantum Systems, a small UAV startup company located near Munich which specializes in fixed-wing VTOL UAV like the Quantum (Fig.1).

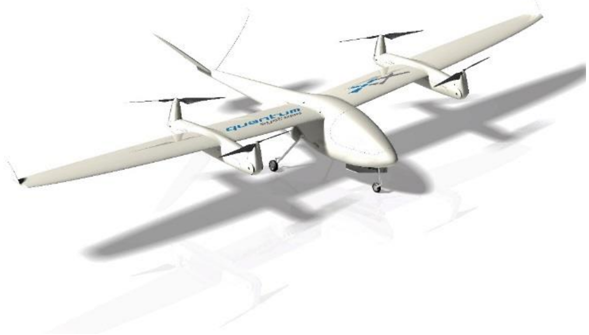


Fig. 1: Quantum Systems first-fixed-wing VTOAL UAV called Quantum

Quantum Systems is thus giving the fictive design bureau named LLS Engineering where the students are employed the task to design such a VTOL UAV to fulfill the UAV Outback challenge requirements. The main goal was to derive concepts that can fulfill the mission, elaborate and optimize them to a state that the configurations can be compared and evaluated to find the most suited one. The main focus should thereby be on the airframe, but all necessary (sub-)systems that influence the performance of the airframe should be considered.

In the following the presented paper first describes in more detail the structure of the practical course followed by a presentation of the design task. Thereafter the procedure and methods used for the aircraft design process are explained and the results of the configuration comparison are shown. The paper concludes with a summary and lessons learned of the practical course.

2 Course Structure

From the beginning, the course was conceptualized as a supplemental course to the Aircraft Design lecture, focusing on the application. The students should work self-organized and autonomously on actual design problems, with just the design problem and supervision given by the course teachers and industry partners. Following the regulations for practical course at the Technical University of Munich, the design course is scheduled to 12 working sessions of three hours per week as shown in Fig. 2. In the kick off meeting Quantum Systems handed over the design task to the students which then had to come up with their own concepts each presented with a three side view. After discussing, refining and selecting of the most promising configurations the students presented their results to Quantum systems in session 4. The three most promising concepts were then commonly selected to be further detailed and optimized during the preliminary design phase. In this phase the students teamed up in four divisions: structure, aerodynamics, simulation, propulsion like in an industrial company. Besides performing their specialized work task they had also to define interfaces between the divisions and schedule their work by themselves. Finally the results of the configuration optimization were presented to Quantum Systems and a written report was handed over.

Fig. 2: Milestones and design phases during the aircraft design practical course

3 Description of the design task: Medical Express UAV Outback Challenge 2016

The example design task described in this paper is to design an UAV for the medical express UAV outback challenge. The medical express challenge is one of the world's largest UAV competitions and takes place every year in Australia. The aim of the challenge is to demonstrate the use of UAV in civil applications, especially in those who can save lives. The requested mission for the challenge held in 2016 is pictured in Fig. 3 [1]. Outback Joe is feeling unwell. After calling his doctor he requested a blood sample. Unfortunately Outback Joes property is very remote and to make things worse it has been cut off by floodwaters. The solution for this situation could be an UAV to help Outback Joe to take his blood sample to the doctor. The UAV has to take off and fly autonomously within a flight corridor to Outback Joe. After detecting his position within a 100m circle the UAV has to land close to Outback Joe. Now he can load his blood sample into the UAV which then takes off and flies the sample back to the medical base. The range covered by the UAV is well over 20km and the total available mission time is limited to one hour.

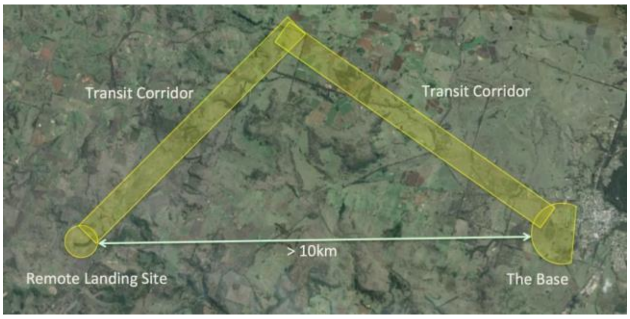


Fig. 3: UAV Medical Express Challenge Mission

The missing infrastructure and vegetation at the takeoff and landing zone requires vertical takeoff and landing. The needed range and limited mission time makes it hard to unfeasible to accomplish the mission with current helicopters or quadcopters. So fixed-wing VTOL aircraft would be needed to enable this mission.

After handing over the task description to the students by Quantum systems, the first task was to analyze the regulations and collect further information like meteorological conditions to derive a requirements catalogue. The main driving requirements are listed in the following:

- Payload Mass: 100g
- Payload dimensions: Cylinder with 20mm diameter and 100mm length
- Easy and safe loading of the payload in less than 1 min
- Range > 60 km
- Mission time max. 60 min, with 50 min cruise, 5 min loiter and 2 min hover with 2 takeoffs and landings
- Ceiling 1500 ft
- Average wind speed of up to 13 m/s
- Cruise speed: up to 32 m/s
- Setup time of the UAV < 15 min
- VTOL capability, 2 takeoffs and landings per mission

To ensure that the design also fits in the portfolio of Quantum Systems they released additional requirements:

- Increased payload of up to 500 g
- MTOW < 5 kg
- Electric propulsion system
- Transportable in a car

4 Conceptual design phase – Configuration evaluation and selection

After deriving the requirements the design process started with the second session. To prepare for it the students had to do a market survey of fixed-wing UAV. This is always a good point to start with because it helps students to get a feeling about the possible design space. Also empirical data can be collected which is valuable to estimate parameters at the beginning of the design process or to do sanity checks of own calculations.

During this session each student had to come up with his own concept suggestion. With a drawn 3-side view of his configuration on flipchart paper each concept was presented to the group advertising the features and benefits of the design. During the following discussion critical or open points where noted down. At the end of this session each configuration was evaluated according to the criteria listed in Fig. 5. In that way the most promising configurations could be determined in an easy and fast way. Furthermore the concepts where grouped in categories:

- Tilt Rotor
- Tilt Wing
- Tail Sitter
- Other

In the third session the task was to further improve and eliminate open points of the highest ranked configurations from each category. Therefore the students were divided in 4 groups and each group refined one concept. The results are shown in Fig. 4:

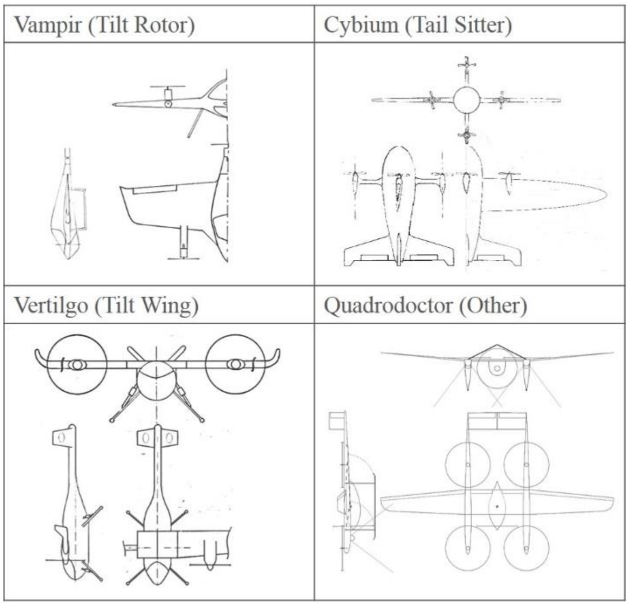


Fig. 4: Refined Concepts

The Vampir is a tilt rotor configuration. It features three propulsion systems. Two are mounted on pods on the wing and one is mounted at the tail of the aircraft. All three propulsion systems are tiltable around the lateral axis. During hover all propellers point upwards. Yaw control can be achieved by tilting the wing mounted motors. During cruise the two front motors are tilted forward and provide thrust. The rear motor is also tilted horizontally and the propeller is folded to minimize drag. The vampire is a flying wing. This reduces structural weight and drag during cruise, whereas the main disadvantage of flying wings, the bad high lift capability for takeoff and landing, is not required for a transition aircraft.

The Cybium is a tail sitter. During hover it is controlled like a quadcopter with its four motors. Additionally it has control surfaces at the empennage to increase authority in gusty conditions, which are a problem for most tail sitters due to their big lateral surface area. During transition the whole aircraft rotates around its lateral axis. This enables on the one hand a simple design without tilt mechanisms but on the other hand also rotates the payload and sensors. This is not favored for some type of missions.

The Vertilgo is a tilt wing concept. Two motors are mounted on the wing. They provide the cruise thrust and vertical thrust during hover while tilted upwards. For hover control there are two additional small impellers integrated in the v-tail.

The Quadrodoctor is a mixture between a quadcopter and a conventional configuration. It has four hover motors in its twin fuselage so it can hover like a quadcopter. For cruise there is a separate motor at the central fuselage pod and conventional aerodynamic control surfaces. The Quadrodoctor is a very simple configuration as it has no tilt mechanisms and the control of hover and cruise can be achieved with independent actuators/motors. This enables also efficient propulsion systems as they can be optimized for their specific tasks.

During the preliminary design phase the central fuselage pod has been eliminated by distributing the payload to the two twin fuselages and installing the cruise motor at the tip of the inverted v-tail.

After finalizing the four concepts a power point presentation of each concept was prepared and presented at Quantum Systems during the fourth session. After a discussion the four configurations had been evaluated qualitatively together with Quantum Systems. The evaluation criteria and their emphasis was commonly agreed as well as the qualitatively distributed points ranging from 1 for very bad to 5 for very good. The results are shown in (Fig. 5).

Evaluation Criteria	Factor	Quadrodoctor	Cybium	Vampir	Tilt Wing
Savety	5	3	3	2	2
Noise	1	4	4	4	3
Payload integration	4	5	3	4	4
Mission universality	3	5	4	5	5
Gust sensitivity	3	5	2	4	4
Setup time	2	5	5	5	5
Easy handling	5	5	5	5	5
Complexity	3	5	4	3	3
Cost	3	4	4	3	3
Efficiency hover	2	5	3	3	3
Efficiency cruise	4	3	2	4	4
Total points		**153**	**122**	**132**	**131**

Fig. 5: Refined concept evaluation

Finally the Quadrodoctor and the Vampir have been selected as the most promising solutions. They have been further detailed during the preliminary design phase described in the following chapter. As Quantum Systems already has experience with their Quantum (Fig.1), this configuration has been additionally selected for benchmarking. The Quantum features four propulsion systems located at the ends of two wing mounted pods. For hover flight the propellers are tilted upwards. During transition all four motors are tilted in a forward flight position. For cruise only the two front motors deliver the thrust whereas the two rear propellers are folded to reduce drag.

5 Preliminary Design Phase - Configuration optimization

To further evaluate also quantitatively the performance of the three selected configurations, they have been sized and optimized for the mission requirements. Therefore the students had to apply for one of the four divisions - structure, aerodynamics, simulation and propulsion - of the fictive design bureau named LLS Engineering. That way an industry working environment was simulated. Each division had the task to provide Matlab tools to calculate their dedicated outputs in dependence of main design parameters like wing surface and aspect ratio: The structure department calculated the aircraft mass, the aerodynamic department the aerodynamic coefficients, the propulsion department the power requirements. Finally those tools have been combined by the simulation division to optimize the design parameters and calculate the mission performance. Besides the technical calculations, a lot more skills are needed to come to a flyable aircraft. The students had to define a schedule as well as interfaces between the departments and had to learn how to clearly communicate between the departments.

5.1 Program Overview

Fig. 6 gives an overview about the configuration optimization and evaluation.

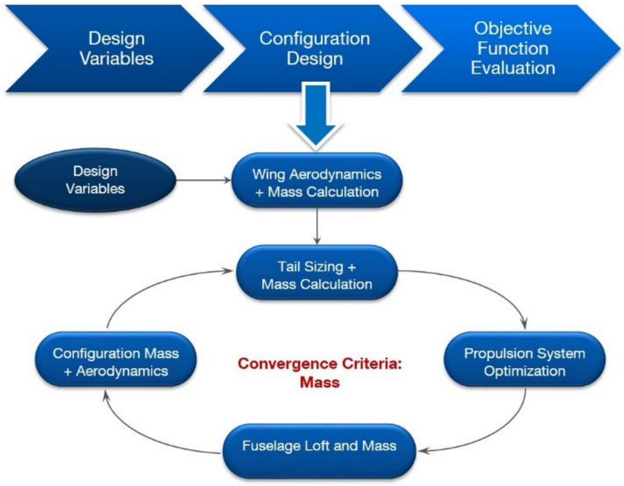


Fig. 6: Configuration optimization overview

First the main design parameters had to be determined. Some, like the wing span or aspect ratio are obvious, others, like the empennage aspect ratio have only little influence on the performance of the aircraft. To determine the most important ones sensitivity studies have been done. To keep the simulation efficient and calculation times well below one day only the most important ones have been selected as design variables:

- Wing surface
- Wing aspect ratio
- Airfoil thickness and camber
- Empennage to wing surface ratio (except for Vampir)
- Thrust ration between front and rear motors

For each set of design variables a configuration has then been designed. The sequence in which the modules are aligned is important because it influences the efficiency of the calculation. If only variables are passed from one module to the next (feedforward information) the configuration can be calculated directly. However, because of the high interdependencies between the modules, backward-fed variables exist, too. This requires an iterative process to converge all variables. The goal is to align the modules in a way to have as less backward-feed variables as possible. Also modules that are sensitive to parameter variations should be aligned more to the end of the iteration loop. There the accuracy of the parameters is already higher because of the calculations of the previous modules. The sequence shown in Fig. 6 proved to be most efficient [2].

First the wing aerodynamic coefficients and mass can be calculated directly. The wing geometry is already defined with the design parameters wing surface, aspect ratio and airfoil thickness and the fixed parameter taper ratio.

The first step in the iteration loop is to size the tail according to the stability margins. Once the size is determined the mass can be calculated. With an estimated mass and glide ration the propulsion system can be selected. With the chosen propulsion component together with all other fixed components, the calculated lever arm of the empennage and the required cg position, the fuselage loft and therefore mass can be determined. In the last step the total aircraft mass and aerodynamics can be calculated. Now it can be checked if the initially estimated mass and glide ratio is met or another iteration loop with the new values must be done.

Once the configuration has converged the objective function can be evaluated. In this case the goal was to minimize the total mass of the aircraft. Since the mission requirements like speed and range are fixed, the mass has been chosen as lighter and therefore also smaller aircraft are cheaper and easier to handle as heavier ones.

5.2 Simulation

The task of the simulation division was to integrate all modules coming from the other division into one simulation and optimization tool. With this tool the design parameters of each configuration have then been optimized. This was done on the one hand through parameter variation. That way the effect of one parameter on the objective function can directly be plotted which is essential for understanding the influence and sensitivity of that parameter. On the other hand a genetic algorithm has been used. Due to discrete variables and some local optima genetic algorithms are very well suited for aircraft design problems and are a good compromise between finding the global optimum and calculation effort.

5.3 Aerodynamics

The aerodynamics department should calculate the aerodynamic drag, lift and moment coefficients of the aircraft and size the empennage. Also they had to choose fixed parameters like the taper ratio of the wings and the tail plane and select an airfoil for the empennage.

For small aircraft viscous effects have a big influence on the drag polar. Therefore viscous airfoil polars were calculated with XFOIL. The polars were generated for different Reynolds numbers for an airfoil family with varying camber and thickness based on the laminar model sailplane airfoil SD7037. The exported txt-files were then imported in Mathlab as lookup tables for airfoil drag, lift and moment coefficient. The lift of the wing could afterwards be determined with the method by Polhamus for unswept high aspect ratio wings at low speeds:

$$C_L = \frac{C_l \cdot \Lambda}{2 + \sqrt{\Lambda^2 + 4}}$$

To the airfoil drag the induced drag was added based on the lift coefficient, aspect ratio and Oswald factor.

$$C_{Di} = \frac{C_L^2}{\pi \cdot \Lambda \cdot e}$$

The wing lift and drag for the vampire is calculated differently. As it is a flying wing, it is important to trim the aircraft, because this has a mayor influence on the coefficients. Therefore the complete wing was calculated with XFLR5. This is an open source tool which includes the viscous airfoil calculation routines of XFOIL and additionally has the opportunity to calculate complete wings with lifting line vortex lattice or panel methods. Wings with different surface and aspect ratio as well as twist for trimming were calculated. The results have been imported to Matlab as a lookup table.

Fuselage drag and drag of pods were calculated with the surface friction method by Raymer [3].

All other drag components like antennas, landing gear, inactive hover propellers and interference drag were calculated by methods of Hoerner [4].

The sizing of the empennage is based on the method described by Quabeck [5] for a defined static margin requirement.

5.4 Structure

The structure group had to fit all required components into the fuselage, determining required volumes and dimensions, maintaining the CG, size the structural parts and finally calculate the mass of the aircraft.

VTOL aircraft are even more weight sensitive than normal aircraft. Therefore the structure should be as light as possible with most advanced composite manufacturing methods. The weight estimation of the structural components is a combination of analytical calculations and empirical data described in detail in [2]. The fuselage mass is calculated by simply assuming a monolithic laminate with constant thickness. The wings are built in a sandwich shell construction (Fig. 7).

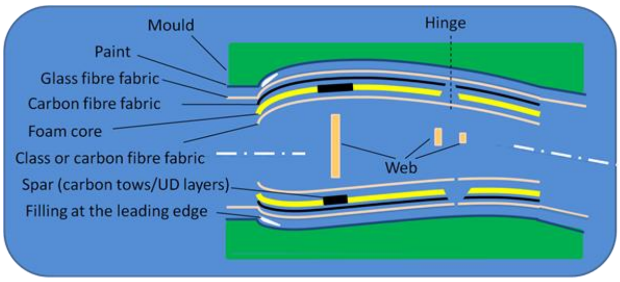


Fig. 7: Wing manufacturing method

The torsional shell layers are sized for maximum allowable wing twist and the spar for maximum g-force for bending. The calculated required thickness of the layers is rounded to the next higher purchasable laminate thickness. All other components like glue and paint are accounted for with empirical equations.

To the structural components the mass of the fixed aircraft systems like autopilot, sensors, data links and payload as well as the optimized propulsion system components are added in the end.

5.5 Propulsion

The propulsion system consists of a propeller, a motor with optional gearbox, a motor controller (ESC) and a lithium polymer battery. For given thrust levels according to the drag calculations and flight speeds based on the mission definition the lightest propulsion system has to be found. As cooling of the propulsion system components was not considered, the most efficient powertrain might not be the best solution but the lightest propulsion system (including battery), to fulfill the mission. That way you get the lightest and smallest possible aircraft.

The motor torque rpm and efficiency is modelled with three motor constants according to Lundström [6]. The constants are the inner resistance, the rotational speed constant and the idle current. Those together with dimensions and mass were collected from different manufacturers in a motor database.

The ESC is modeled as an ohmic resistance for full throttle. For part throttle an empiric combined motor ESC model according to Rößler [2] is used.

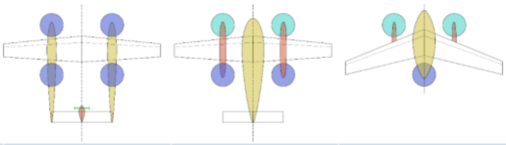
For each motor an optimum propeller to match the motor and fulfill the mission requirements was selected from a lookup table with different diameter and pitch propellers. It contains data for thrust, rpm and torque for each propeller at different flight speeds. This table was generated with XROTOR and imported to Matlab.

After determining the power consumption for the different mission segments and summing them up to a required energy for each motor propeller combination a battery was chosen from a database.

Finally the lightest propulsion system as a combination of propeller, motor and battery was chosen.

6 Results – Configuration Comparison

The three developed UAV concepts were optimized with the described tool with regard to their total mass. For the calculated optimal solution, the selected optimization parameters and many other configuration data were saved as a readable file. Some important parameters are shown in Fig. 8. Based on this, the basic aircraft characteristics become visible and the various concepts can be comparatively assessed with regard to the suitability of the desired objective.



	Quadrodoctor	Quantum	Vampir
Mass	5,02 kg	4,83 kg	4,41 kg
Wing Surface	0,16 m²	0,12 m²	0,20 m²
Aspect Ratio	13	18	10
Span	1,44 m	1,47 m	1,42 m
Fuselage Length	0,81 m	0,63 m	0,27 m
Glide Ratio	1:10,5	1:13,5	1:13,5

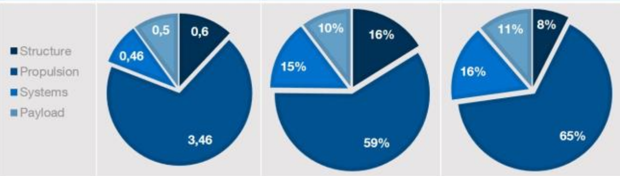
Fig 8: Selected configurations with optimized main geometric results. The propeller color defines the type of propulsion system: Hover, Hybrid, Cruise

With 4,41kg, the 3-rotor UAV concept Vampir best meets the requirement for a low total mass. The Vampir achieves a significantly better result with over 400g mass saving compared to the Quantum concept. The Quadrodoctor is slightly above the weight limit of 5kg.

The dimensions of all configurations are basically very similar, especially the span moves in a very small area. However, the Vampir has a much shorter fuselage and of course no tail. The wing area of the Vampir is the largest because as a flying wing it can't archive as high maximum lift coefficients as the conventional configurations. The wing area of the Quantum is the lowest. This is also due to the very high aspect ratio of 18 and therefore very efficient wing. Looking at the data the influence of the aspect ratio on size and mass is very low in a range between 14 and 18. With an aspect ratio of 14 also the wing area would be similar to that of the Quadrodoctor, only slightly lower due to the lower overall mass. The aspect ratio of 10 of the Vampir is a bit lower due to the lower lift coefficients.

The aerodynamic efficiency (inverse of the glide ratio) of the Quadrodoctor is slightly lower than that of the other two configurations. The drag is higher because of the high wetted surface area due to the twin fuselage, but mainly due to the hover propellers that are only aligned in flight direction during cruise but not folded or covered.

For a closer look, the distribution of the masses on the various aircraft components is shown in Fig. 9.



	Quadrodoctor	Quantum	Vampir
Structure:	0,60 kg	0,78 kg	0,33 kg
Propulsion:	3,46 kg	2,85 kg	2,88 kg
Systems:	0,46 kg	0,70 kg	0,70 kg
Payload:	0,50 kg	0,50 kg	0,50 kg
Total:	**5,02 kg**	**4,83 kg**	**4,41 kg**

Fig 9: Mass distribution of the optimized configurations

The Vampir as a flying wing concept has a considerably lower structural mass. This is the main reason for the lowest total mass in the overall comparison. The high mass of the Quadrotoctor can be explained as following: The functions of the drive units during hovering and cruise flight are strictly separated which makes them very efficient and leads to a low battery mass. However the additional mass of the separate motors for each flight state leads to a higher overall propulsion system mass. Also the lower systems mass due to no tilt mechanisms can't prevent the result of the highest overall mass of all configurations.

The final decision which configuration is best for the medical express challenge mission is hard to say in the end. The Vampir has a simpler structure and is the lightest configuration but as a tricopter flying wing might not be as easy and robust to control as the Quantum. However the technological simplest concept is the Quadrodoctor, which is the reason that this configuration can widely be found as fixed wing transition VTOL concept.

7 Course Summary – Lessons Learned

In the practical Course Aircraft design at Technical University of Munich a concept study of fixed-wing VTOL UAV for the medical express UAV challenge was performed. The up to date design task and the cooperation with the industry partner Quantum System highly motivated the students. In the first phase of the course the students had to sketch their own configuration ideas and learn to present them to others. In the second phase an industrial environment with specialized departments working together on one project was simulated. In this phase the students had to practice and expand their knowledge learned in lectures. They experienced that aircraft design is an iterative process with strong interdependencies between the different disciplines. By varying the design parameters they learned the sensitivities and effects of changing them in the one and other direction.

Besides the technical aspects the special setup of the course emphasized the use of soft skills like team work, self-organized working, time planning, and presentation and communication skills. Those aspects are finally summarized in Fig. 10:

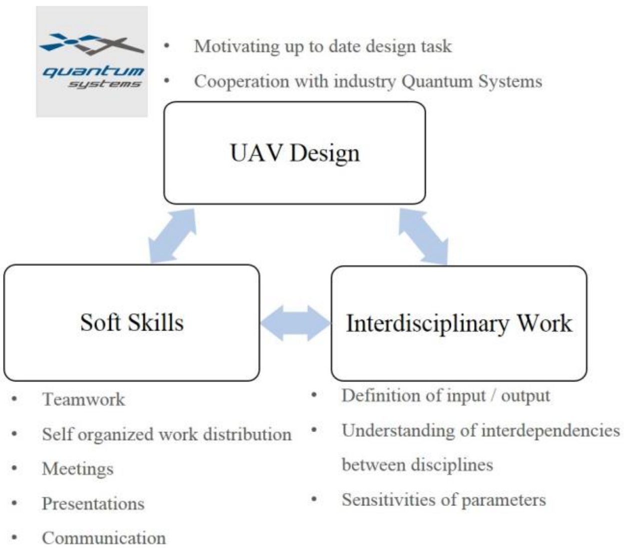


Fig 10: Conclusion and lessons learned

Acknowledgements

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