Lessons Learned 3, 1 (2023)
Submitted: 14.10.2022
Accepted: 23.12.2022
DOI: https://doi.org/10.25369/ll.v3i1.59
ISSN: 2749-1293 (print); 2749-1307 (online).

From the Computer into the Air - The Interdisciplinary Design Project Aerospace Engineering

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Abstract

As part of the Interdisciplinary Design Project Aerospace Engineering, students design unmanned aerial systems (UAS) for search and rescue missions. This includes preliminary design (e.g. aerodynamics), detailed design (e.g. autopilot design) and, so far, simulation-based verification of the overall concept. Now the design is to be brought from the computer into the air. For this purpose, the Chair of Flight Mechanics and Flight Control provides all electronic components (engines, flight computers, etc.). The aircraft structure is to be manufactured by the students themselves. For this purpose, they have a state-of-the-art laser cutter at their disposal, which the professorship received funding for within the framework of the call for proposals for teaching/learning projects of the Faculty of Mechanical Engineering. This allows the fast and efficient cutting of the structural parts in wooden construction. The self-built UAS is evaluated in a flight test.

Im Rahmen des Interdisziplinären Entwurfsprojektes Luft- und Raumfahrttechnik entwerfen Studierende unbemannte Flugsysteme für Such- und Rettungsaufgaben. Dies umfasst den Vorentwurf (z.B. Aerodynamik), Detailentwurf (z.B. Autopilotenentwurf) und, bisher, die simulationsbasierte Verifikation des Gesamtkonzeptes. Nun soll der Entwurf vom Computer in die Luft gebracht werden. Hierfür stellt die Professur für Flugmechanik und Flugregelung sämtliche elektronischen Komponenten (Motoren, Flugrechner, etc.) zur Verfügung. Die Flugzeugstruktur soll von den Studierenden selbst gefertigt werden. Hierfür steht ihnen ein hochmoderner Lasercutter, welchen die Professur im Rahmen der Ausschreibung für Lehr-/Lernprojekte der Fakultät Maschinenwesen gefördert bekommen hat, zur Verfügung. Dieser erlaubt den schnellen und effizienten Zuschnitt der Strukturteile in Holzbauweise. Das selbstgebaute Flugsystem wird im Flugversuch evaluiert.

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This article was originally submitted in German.

1. Introduction

The module "Interdisciplinary Design Project Aerospace Engineering" ran for the first time in the summer semester of 2022 at the Chair of Flight Mechanics and Flight Control, which has been in existence since January 2021. As part of the project, students work in groups of four to design and test a small Unmanned Aerial System (sUAS) specifically for search and rescue missions – an ever-growing field of application for sUAS. The current iteration stage consists of the three core topics of any design project: the preliminary design, the detailed design and the implementation and verification of the concept. The latter, however, is still done purely numerically within a simulation environment. The project demands a high degree of teamwork, self-organization and interdisciplinary thinking from the students. The direct interaction with each other, but also with the lecturers, promotes the development of essential soft skills from which the students can benefit in their later careers. The work and consultation in a small group format makes it possible to closely monitor the learning progress of individuals, to provide targeted support and also to challenge them. A core aspect of the course is a realistic implementation of the design project, which includes reasonable requirements, development of specifications, reviews, progress meetings and presentation of milestones. In the next evolutionary stage of the project, the designs will now be taken from the computer to the air. The students will build their aircraft designs using structural parts manufactured with a laser cutter. The chair provides commercial-off-the-shelf (COTS) electronics components. A final flight test campaign will then verify the flight characteristics of the designs. This will allow students to go through the complete design process of an sUAS and earn the rewards of their work.

2. The current iteration stage

The "Interdisciplinary Design Project Aerospace Engineering" started in the summer semester of 2022: Groups of four students each design a small unmanned aerial system for search and rescue tasks. A fixed-wing configuration was chosen consciously for this purpose because it is the most efficient and most-commonly used configuration for such tasks. It also allows direct, interdisciplinary application of the theory taught in the aerospace course including aircraft design, structural design, flight mechanics, flight dynamics, flight performance, flight control, as well as aerodynamics. Furthermore, sUAS represent one of the major growth markets of the international aerospace industry [1], but receive little attention in the teaching of many universities so far. Thus, the module perfectly prepares students for a potential career path and gives them an edge over competitors from other universities. This specific outlook directly contributes to student motivation and engagement.

Especially in a course based on personal responsibility and self-organized work, it is important to convey a comprehensible story and a realistic scenario. This represents the starting point of the project, in which the teachers act as the company's management and the students embody a team of young development engineers facing their first major project after receiving their degree.

The company management presents a customer's order for an sUAS for a well-defined reference mission (Fig. 1) with imposes performance requirements which differ slightly for each group. Special attention was paid to fair conditions, i.e. no requirement was per-se more difficult than another. However, they were different so that there was no suitable "standard design" for all groups. Based on the given requirements, a defined specification was presented.

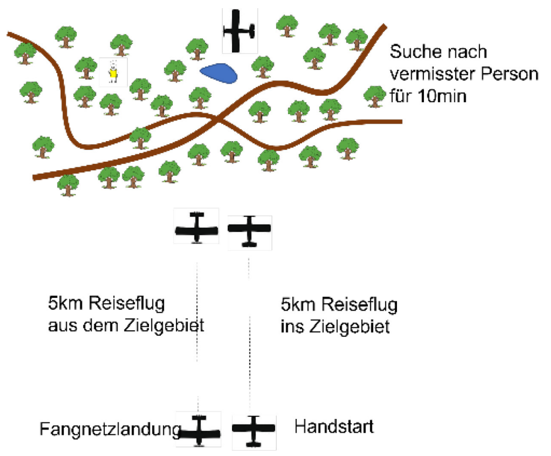

Fig. 1: Example mission of an sUAS

This marks the start of the project, which in its current state consists of three main parts: the preliminary design, the detailed design and the simulation-based verification of the overall concept.

In the preliminary design, students must fundamentally dimension their sUAS based on flight performance and aerodynamic calculations. This includes the selection and evaluation of a suitable airfoil and planform. For the former, the program XFoil [2] is used. This tool is based on a 2-D panel method with superimposed boundary layer calculation and allows the numerical computation of airfoil drag polars as the basis of the overall aircraft velocity polars. These are mandatory for the selection of the propulsion system, batteries and determination of the flight performance. For this purpose, the students are given data of COTS motors and batteries as well as typical assumptions for the preliminary design regarding aerodynamic drag or structural masses of individual aircraft parts. This keeps the focus on the design and the task within a reasonable time frame. All calculations are performed in Matlab [3], one of the most powerful and widely used engineering computation and simulation tools in the industry. The presentation of the results is equivalent to the "Prelimenary Design Review" (PDR) in an industrial project.

Matlab was selected intentionally as the software of choice, as briefly explained below. On the one hand, Matlab is the leading commercial software for numerical simulation and data acquisition as well as their evaluation. A large number of problem-specific libraries, e.g. for system identification, controller design and controller analyses, allow a broad application to engineering problems, which is why it is used by companies such as Airbus in the field of flight mechanics and flight control or by BMW for the modeling of vehicle dynamics and the development of driver assistance systems. Many university spin-offs in the field of sUAS (e.g. Phoenix Wings, Amazilla Aerospace) also use Matlab. The same applies to research institutions such as the German Aerospace Center (DLR). By familiarizing students with this powerful software at an early stage of their career, it makes it easier for them to start their careers later on. In addition, Matlab uses a syntax that is easier to learn compared to Fortran or C. The software is also easy to use. In combination with the large repertoire of tutorials, it offers students a pleasant learning curve. This is especially important since the focus of such a project should not be primarily on learning how to use software, but on problem-based application of previously acquired knowledge. Last but not least, Matlab includes the software Simulink, which is defacto a graphical representation of Matlab code in the form of block diagrams. Simulink is particularly suitable for modeling and analyzing complex nonlinear dynamic systems. Through direct integration with Matlab, as well as a variety of tutorials, an appropriate learning curve for students is also achieved. Simulink becomes essential especially in the later analysis phases.

The next task block involves the detailed design and thus the final dimensioning of the aircraft. The groups must design a fuselage that can accommodate the payload and the necessary equipment. In addition, the tail unit must be designed to guarantee stability and controllability for all envisioned center-of-gravity positions of the aircraft. Furthermore, a well-founded material selection is required. For the later implementation of the aircraft in the simulation environment, the mass distribution and the aerodynamic characteristics of the sUAS must be determined. For this purpose, the students use the program Athena Vortex Lattice (AVL) [4], which calculates the relevant aerodynamic parameters by means of a vortex-lattice method (Fig. 2). AVL provides nondimensional coefficients that can be fed into the simulation tool.

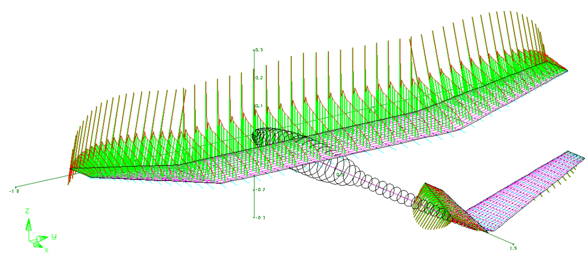

Fig. 2: Example sUAS in AVL

The results achieved to this point represent a major milestone on the way to the project's Critical Design Review (CDR); the final designs are already taking shape (Fig. 3).

Fig. 3: sUAS before the CDR, still without the later V-position of the outer wings (cf. Fig. 6).

Subsequently, the implementation in the modern nonlinear flight simulation environment of the chair based on Matlab/Simulink is carried out. The flight performance data achieved by the nonlinear simulation are compared with the theoretically achievable ones.

In the final section of the project, last incremental changes are made to the design and the flight dynamics of the aircraft are evaluated using common flight test techniques. Based on the knowledge gained in the lecture Flight Mechanics and Fundamentals of Aerodynamics/Aerodynamics and a short recapitulation in System Dynamics, the aircraft's eigenmodes in longitudinal direction (phygoid and angle-of-attack oscillations) and lateral direction (spiral motion, roll motion and Dutch roll) are characterized. Here, methods such as the transient peak ratio [5] are used to identify natural frequencies and damping of the eigenmodes. These are directly related to the aerodynamic design of the aircraft and therefore the results from AVL. These results are compared with common requirements from the so-called "Mil-Specs" [6]. This way, the flight dynamic performance of the aircraft without a controller can be assessed. If this is not sufficient, (minor) aerodynamic modifications have to be made to the design. This part of the project requires a high degree of interdisciplinarity and transfer performance from the students.

This is followed by the design and implementation of the flight controllers for longitudinal and lateral motion. The purpose of the controllers is to further improve the flying and handling qualities of the aircraft, as well as to augment the controllability for the operator. The designs will be limited to classical proportional-integral-derivative (PID) controllers. PID controllers are familiar to students from undergraduate courses, allowing them to rely on existing knowledge. Extensive numerical tests are performed to compare the behavior of the closed-loop and open-loop aircraft. The comparison of the controlled and uncontrolled aircraft is shown in Fig. 4. At the end of the block, a milestone is reached which corresponds to the CDR in an industrial project.

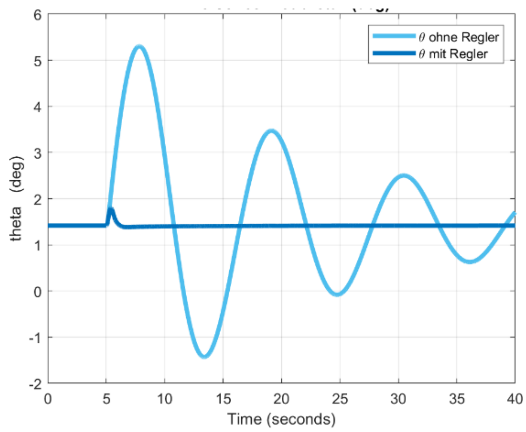

Fig. 4: Time course of the pitching motion after a wind disturbance without and with controller

Students are supported in working through the tasks and milestones in two individual group consultations of 30 min each in every block. This allows the teachers to assess the individual group progress as well as to specifically support students in their scientific development.

With a report and the final presentation after each block, the presentation of results in front of larger groups is trained. A very important skill which is often neglected at universities. Additionally, the active exchange between the groups by means of constructive feedback should be promoted.

3. Student feedback and lessons learned

Although the first iteration of the project is still limited to a purely theoretical and simulation-based implementation, all participants have shown a high level of interest and strong commitment from the very beginning. There was a good and stable participation of the twelve registered students in the lectures in off-peak hours (Tues., 16:40-18:10 and Fri., 7:30-9:00), while the audience for the conventional lectures was slow to find their way back into the lecture halls. This makes the course an important component of the Mechanical Engineering Faculty's back-to-campus strategy.

Particularly the consultations encourage an intensive exchange between teachers and students, which has suffered greatly in times of purely digital teaching. This is essential in the first iteration of a new course, as it allows the teachers to identify the students' interests and abilities, but also deficits in the structure of the course and potential for improvement.

The feedback given was incorporated directly into the course by the lecturers, resulting in a very dynamic and also modern event. For example, the number of reports was significantly reduced towards the end of the lecture period and more compact milestones were formulated, as they are also common in industry. A further "industrialization" of the task blocks and their "milestones" and "deliverables" is planned in the next iterations of the module (Fig. 5).

This adjustment allowed students to spend more time on the design tasks. However, the regular presentations remained. These presentations have received very good feedback and students have welcomed the opportunity to improve their presentation skills in front of a critical professional audience. This was noticeable in a steady increase in presentation quality and hence an improvement in an important soft skill.

Moreover, the presentations are an adequate means to motivate the groups to work continuously and to prevent "high-pressure" work shortly before the submission deadline of the document. This was very positively received by the participants.

The students also found it positive that time-intensive and iterative work, which required coordinated homework, took place at the beginning of the semester. Shorter and especially more practical tasks towards the end of the semester could avoid additional stress before exam time.

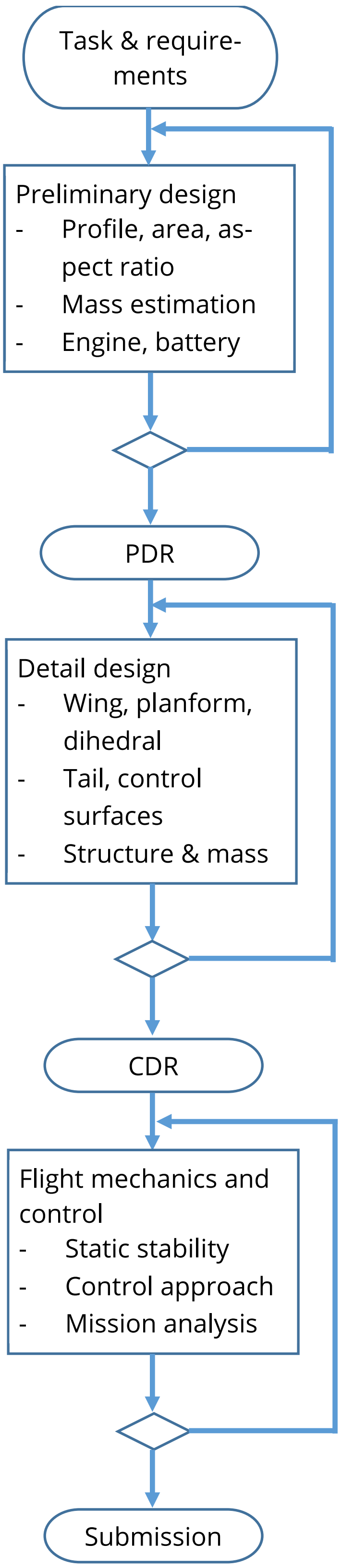

Fig. 5: Flow chart of the project process

Furthermore, the presentations and frequent consultations are very suitable for quickly evaluating the progress of the groups. In this way, risky concepts could be identified, modified accordingly. This way, creativity could be directed efficiently, preventing demotivating and time-consuming mistakes in the process. The success was evident in the designs of all groups, which consistently met or even exceeded all requirements.

Despite the purely theoretical design so far, working on one's own project has a very motivating effect compared to recalculating given academic examples. The highlighting of the different aspects of the design further promotes holistic thinking and understanding of the interactions between the individual disciplines.

Fig. 6: Final design of the group with V-position in the outer wings to improve spiral stability.

Fig. 7: Final design of another group

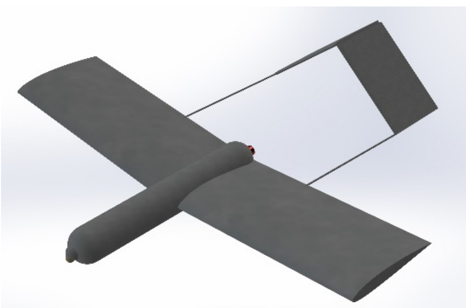

Fig. 8: Final design of the third group

Furthermore, the students have and take significantly more freedom, which promotes creative engineering problem solving. This was evident in clearly different aircraft concepts (Figs. 6, 7, 8).

Moreover, the students welcomed the use and application of various tools. Through lively exchange with the groups, new approaches to the creation of efficient tutorials for self-study were conveyed. The greatest difficulties were encountered by the participants in dealing with Matlab. However, clear progress was observed in all groups over the course of the semester. The interaction in the groups, consisting of participants from different semesters with different interests and abilities, also had a positive effect. This again showed that the whole is more than the sum of its parts and that group work should be an important part of the studies.

An important finding of the first iteration of the design project was its positioning in the curriculum. Scheduled for the eighth semester, it takes place simultaneously with the lecture Flight Dynamics and Flight Control and the module Aircraft Aerodynamics (also provided by FMR). This offers theoretical synergy effects, which unfortunately did not manifest themselves. Since the knowledge imparted in the other two lectures could not be assumed, a dynamic adjustment of the expectation horizon was made on the basis of imparting basic knowledge. A formal shift to the ninth semester could remedy this.

4. Outlook

With the capacities created by the funding within the framework of the teaching project, it will be possible to put the student designs into the air for real, thus allowing all participants to earn the fruits of their hard work.

For this purpose, the Chair of Flight Mechanics and Control plans to procure various components as well as tools for building the drones at its own expense. This includes sets of electric motors of different power, accumulators, servo actuators, flight computers, receivers, transmitters as well as material. The teaching project funding will be used to procure a modern laser cutter, which will enable fast, safe and low-waste production of the individual parts.

Students provide the technical drawings for cutting. Guided by a staff member, they work on the manufacturing process and get feedback on their drawings. After assembling the structure and integrating all components in the chair's UAV lab, students test their own aircraft on a model airfield. Doing so, they will experience the complete, industry-related development cycle of a UAS first-hand and are always actively involved. This ideally prepares the students for employment in the constantly growing commercial UAS market.

Furthermore, it is intended to complement the series of events with wind tunnel measurements on the finished aircraft models. The 3m wind tunnel of the TU Dresden– operated by the chair – has the optimal dimensions for the investigation of objects of this size class (Fig. 9). It will therefore be possible to verify the aerodynamic data obtained with the computational tools and feed them into the simulation environment, whereby the comparability with free flight will improve. For the relatively low forces to be expected regarding the low velocities, a suitable balance still has to be made available. Its construction and calibration will be the subject of a student research project. In addition, particularly the assumptions regarding the efficiency of the propeller, on which the design of the propulsion system is based, still seem quite optimistic. Student work on the measurement of propeller characteristics in the wind tunnel is also planned for this.

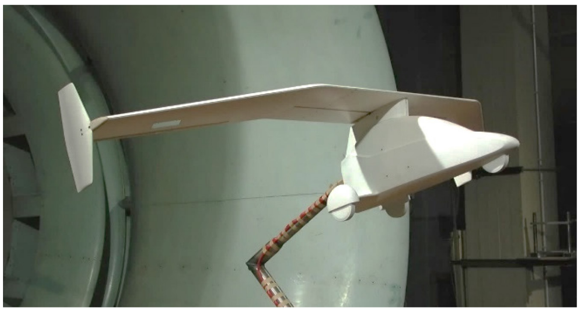

Fig. 9: Model of a tailless aircraft with a wingspan of about 2 m in the wind tunnel of the TU Dresden

Finally, the iterations in the design part are reduced by setting more specific and partly more restrictive reference values and less iterative calculation approaches in order to approximately maintain the time frame of the lecture.

With the overall higher practical component and the motivating prospect of being part of a team that makes an airplane fly, it is expected that the number of participants will increase significantly compared to the first attempt.

Acknowledgement

The authors would like to thank the Faculty of Mechanical Engineering of the TU Dresden for funding the laser cutter within the framework of the "Call for Teaching/Learning Projects of the Faculty of Mechanical Engineering".

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