Experiences using autonomous model airplanes for embedded control education and for bachelor and master theses projects

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***Abstract*—We present experiences with developing an autonomous airplane from scratch including all the avionics and why we focus on an UAV as an application for educating skills in electronics or control theory. The reasons for the selection of the type of aircraft are discussed in detail. Our avionic system is presented consisting of an inertial navigation system coupled to a GPS receiver, a half duplex 433 MHz link and an ultrasound landing guidance system. All electronics are developed in-house. For simulation and control design the Matlab/Simulink environment is used. The 3D simulation output is done by a network link to the open source flight simulator FlightGear and by a graphical 3D Simulink output window.**

***Index Terms*—Control engineeering education, UAV, model airplane, avionics, inertial navigation system, flight simulation, best practice.**

I. INTRODUCTION

The first fully integrated MEMS gyroscope, introduced by Analog Devices in October 2002 [1], in conjunction with already available MEMS acceleration sensors and electronic compasses, enabled for the first time the development of really small and lightweight Attitude and Heading Reference Systems (AHRS), that used to be heavy and expensive before. An AHRS with a GPS-receiver, assistive radio control and other sensors, builds the heart of the avionic system of a modern unmanned aerial vehicle (UAV), an aircraft which can fly radio controlled but in most cases is also intended to fly autonomously. Until the 90's (large) UAV's were mainly of interest for military use, but with the new, lightweight MEMS AHRS's it was possible to shrink the size of autonomous UAV's to that of small model aircrafts and beyond, the smallest weighing only a few grams. The advances in clean and silent electric model aircrafts, like high energy density lithium polymer batteries and high efficiency brushless DC motors did the rest. Many universities, like ETH Zürich [2] or MIT [3] have established UAV groups, dedicated to the research on this new class of aircraft, also called MAV (Micro Aerial Vehicle). Airplanes, helicopters and quadrocopters were built, analysed and programmed to fly autonomously and a lot of scientific papers, master theses and doctoral theses were and are written about UAV's.

But UAV's are not only of scientific interest, they increasingly become a possible application for the education of electronics, radio data transmission, control engineering, object recognition or artificial intelligence in a similar way as we can see it with the well known soccer or sumo robots. Like with these, UAV competition series have started all around the world and they are experiencing impressive growth rates. Examples are the International Micro Air Vehicle Conference and Flight Competition [4] held in Germany or the International Aerial Robotics Competition [5] in the USA.

Although the technical skills could be practised on simpler applications, UAV's have the advantage to exercise a strong fascination on students and applicants, their professors and the public. They rise the motivation and with the right marketing UAV's and other mobile robots have the potential to attract more students for technical universities in general and especially for our University of Applied Sciences Technikum Wien.

II. THE UAV TEAM AT THE UNIVERSITY OF APPLIED SCIENCES TECHNIKUM WIEN

The Department of Embedded Systems at our University established it's UAV team in September 2007 with five primary objectives:

- to get challenging, attractive **bachelor and master projects** where most skills of electronic education could be practised
- to build impressive, functional models to **promote our university** at public technical shows and contests
- to **attract more new students** for the university and for our master programme
- to develop interesting **educational models and course materials** for our courses like the two term embedded control course
- to **provide key components** like the inertial navigation system or the telemetry system for other projects and degree programmes

This project is founded by the City of Vienna, department MA27, under grant "Sponsored Professorship Embedded Control and Navigation".

The team currently consists of students from four different degree programmes working on their bachelor or master theses in their last year of study and the team leader and founder Thomas Kittenberger. The team members change each year, new members are selected and introduced in May and June and work on the project and their theses from September to next June. Some students were team members with their bachelor projects as well as with their master projects.

The team started with three master theses on the development of a MEMS based attitude sensor. In study year 07/08 the electronics, the simulation and calibration procedures and a computer controllable rate table for calibration were developed. In study year 08/09 the UAV-Team grew to two master and three bachelor students. They designed a new, flat inertial navigation board, improved the INS calibration so that also a short term position integration is possible and added a GPS receiver for long term positioning. Also the hardware for several other sensors like ultrasound ranging, barometric altitude measurement, battery monitoring or propeller speed measurement was developed. For telemetry a 433 MHz COTS transceiver module was used at first, which was replaced later by a transceiver module developed at our department. In the last year 09/10 the team consisted already of three master and six bachelor students and produced about 500 pages paperwork (which had to be proofread in only a few weeks). The main aim was to install the new avionics hardware on an appropriate model aircraft and realise autonomous flight including take off and landing.

III. Selecting an Appropriate Aircraft

An important and far-reaching decision is the choice of the type of aircraft. We wanted to have a simple and robust construction that was capable to fly indoors and outdoors with a gross weight in the range of 300 to 500 grams to be capable to carry all the electronics. The price shouldn't be too high to avoid a golden sample nobody dares to fly and the propulsion should be done with LiPo batteries and brushless motors.

Helicopters with that weight need already larger size and high speed rotors. The kinetic energy in the rotor blades presents a serious safety issue. An accident can seriously harm students and a broken helicopter is quite expensive to repair. This type of aircraft is only appropriate for experienced teams but not for beginners and in classroom use you have each year new beginners.

Quadrocopters have typically four smaller and safer rotors and the overall complexity is simpler compared to that of a helicopter. Therefore they are better suited for use in electronic education and they are also quite common in the UAV scene. The attitude control is either done by regulating the speed of each motor, what leads to slower response times, or by using variable pitch propellers similar to a helicopter, what makes them more complex and expensive. Because they use simple, less dangerous propellers beginners can fly them indoors as well as outdoors. If the propellers are mounted on a propsaver (rubber band) a hard landing can results in no damage at all or just a simple propeller has to be exchanged. A real crash would destroy the construction, brake the servos and possibly bend the motor shafts. Looking at the price of a full blown variable pitch quadrocopter compared to that of a simple fixed wing aircraft that seemed to risky and expensive to us.

Fixed wing propeller airplanes are the oldest and simplest aircrafts heavier than air. With lightweight LiPo batteries and brushless motors modern 3D acrobatic airplanes are also able to hover vertical like a helicopter, even in small labs, although they use a single small size propeller like a quadrocopter. Instead of four propulsion units consisting of motor, propeller and electronic speed controller, just one propulsion unit is necessary. The fuselage and the wings can be made of cheap an lightweight synthetic foams like extruded polystyrene (EPS) or the viscoplastic expanded polypropylene (EPP), which forgives smaller impacts and is easy to glue if it comes to severe crashes. And if it comes to outdoor level flight an airplane just looks nicer than any other flightgear.

Looking at the above aircraft type evaluation it is clear that from our point of view a classic airplane made of EPP foam would be the best choice. We selected the MS Composit Unique, consisting of EPP wings and fuselage, EPS rudder and elevator and a steel wire landing gear. The wingspan is 94 cm and according to the manufacturer the flight weight should be 320 to 450 grams. The airplane is now powered by an AXI 2217/16 with an 10x4.7" APC Slow Fly propeller and a 3s LiPo battery with 1500 mAh. The gross weight including all our electronics is 650 grams, much more than it should be. At hover flight the motor draws about 13 A. In Figure 1 you see the current setup of our airplane including motor, propeller and the three avionic boards. The battery and the right wing airflow and altitude sensor are missing.

Figure 1. UAV of the Department of Embedded Systems.

After one year of work with this airplane we have made a lot of experiences and we hope it is interesting for you to look back with us at our thoughts from the start of this year and forward to our plans for the next year.

Our decision to select a fixed wing aircraft for level and hover flight turned out to be right. But a fixed wing aircraft hasn't always to be a classic style fixed wing aircraft. The level flight worked perfectly but with hover flight we had some problems. To stabilize the airplane on the roll axis in hover flight the ailerons counteract against the moment induced by the propeller. Depending on the mostly large deflection angle of the ailerons the airstream on rudder and elevator gets heavily disturbed. This induced a strong coupling from the roll control loop to the yaw and pitch control loops. We think that the best solution to this problem would be the change to another aircraft type not considered by us so far, a delta wing aircraft with a shape like a fighter jet. After this idea we found a lot of slow fly delta aircrafts when looking specialised shops. They combine the two ailerons and the elevator to two elevons at the back of the plane. The rudder stays the same. Synchronous control angles on the elevons act as elevator, antisynchronous angles act as aileron. The airstream from the propeller in hover flight mode is always the same on the elevons and the coupling between the control loops is reduced. Other advantages of delta wing airplanes are that it is easier to get large wing surfaces and low wing loadings, that they are not so sensitive to aerodynamic stall like classical wings and that the construction can be very simple when using flat EPS sheets, stiffened by carbon rods. If the rudder is extended to both sides of the delta wing you get a tail sitter aircraft which can also start and land vertically.

Another important point is the weight of the airplane. In summer 2009 we thought that 300 to 500 grams would be a realistic range for our plans. With the avionics boards, motor, propeller, speed controller and battery we ended near 600 grams. On a longer lasting hover test it happened that we lost thrust, we increased the power and lost more thrust. After stopping the motor we realised that it had got really hot. An inspection of the motor revealed that the bearings were okay but the magnets had lost a lot of their power. We found that the maximum temperature for the used neodymium magnets is 80 degree Celsius. Above this temperature they begin to loose their magnetisation which demands more current for the same torque which increases the temperature and so on. The primary cause was the missing airstream in hover mode that cools the motor otherwise in level flight mode. So we added a cooler fan normally used for motors that are used in helicopters and we increased the size of the motor because it seemed to be on his power limit which resulted in a gross weight of near 650 grams.

The point here is not that 650 grams, the point is the cycles you get caught in, always increasing this and that by trying to reach the demanded performance in thrust, payload or battery runtime. In a typical well-balanced airplane design the parts motor, airframe, battery and payload in form of the avionic system have rather fixed mass ratios. Starting with a half weight avionic system could end in a half weight airplane.

Lightweight and small aircrafts are important for a lot of reasons if they are intended for educational purposes. They are cheaper because motor, speed regulator and battery can be smaller. You can build more aircrafts for the same budget and it hurts less if you lose same by crashes. They are easier to transport and store, in the lab as well as on the way to an airfield or a competition. And most important, they are less dangerous. We had to learn that the hard way. Our current 650 g thrust 140 W propeller hit a student without safety gloves on the hand while he was working on control loop adjustments in hover mode. The resulting wound had to be sewed in hospital. On another occasion a thin propeller was unintentionally driven above his specified maximum rotary speed, the blades started to resonate and one blade dismounted and was shot against a wall. Nobody was injured. So take the advice, always wear safety gloves, safety goggles and if possible a coat when experimenting near running propellers. Or even better, try to avoid being in the rotary plane of the propeller.

Another aspect to regard is an adequate place for test flights. Our labs were okay for hover mode flights, but for level flight even large labs or gyms turned out to be too small because of the heavy weight and our missing flight experience. With 650g, a wing span of 94 cm and a wing area of 14.1 dm^2 the resulting wing load is 46 g/dm^2, what requires velocities in the range of 10 to 12 m/s for level flight. We did most of our test flights at a recreation area near the university. Not the best place considering all the other people enjoying their leisure time there and apart from potential legal issues. If possible a dedicated airfield should be the place of choice. If not, a slow flying 200g airplane would be much better than a fast flying and 650g heavy one. In winter or with windy weather a low wing load would also simplify or even enable indoor flight in a large hall or gym.

The last point we want to discuss is the number of aircrafts used. At the beginning of the last study year we wanted to build two or three aircrafts and even more avionic boards to be able to work in parallel and to have spare aircrafts if one crashes severely. We started with the development of boards and software, built our first airplane and as time went by we got more and more behind our schedule. We accomplished to assemble additional boards but there were no time until the end of this year to build a second airplane. We had good luck that no severe crash occurred but near final project presentation we felt quite unwell with that risk in mind. In the next year we will build our new airplanes right at the beginning and select a simple construction so that a few new airplanes can be built in a day. It would also be helpful to choose a modular design where you can change the avionic board(s) quickly from one airframe to another.

Summing all this up we plan following improvements for the next project year:

- switch from a classic wing design to a delta wing design to avoid problems with the airstream on rudder and elevator
- build the airframe in house using EPS-sheets and carbon rods, use a very simple modular design which allows to exchange airframes and avionic boards easily
- build several airplanes and avionic boards at the beginning, there will be no time for that at the end
- tune the properties of the aircraft: similar wingspan, slightly larger wing area, much less weight, the aim is to reduce the wing load from 46 g/dm^2 to 10-15 g/dm^2 and to reduce the minimum level flight speed
- develop a new avionic board with drastically reduced weight, choose a centralised single processor design instead of the current modular multi processor design

IV. THE AVIONIC SYSTEM

UAV's require much higher cognition of their environment than other robotic vehicles. One way that can be accomplished is with an array of wall mounted cameras and an image processing system to compute the position and orientation of the airplane. The MIT Aerospace Controls Laboratory [3] for instance uses that approach. It has the drawback that it works only indoors in the laboratory environment but the advantage that the airplanes can be built much more lightweight.

Another way, we chose for our project, is to measure all required parameters on board of the airplane. A whole bunch of sensors is needed for that task. Figure 2 shows the system concept.

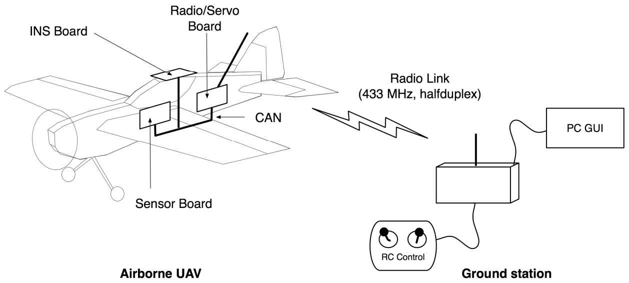

Figure 2. System concept with ground station and remote control unit.

Our inertial navigation system with GPS-support, that was built from scratch at the department over the last three years, is capable to detect the orientation, position and heading of the airplane. A triangulation method based on ultrasonic ranging allows autonomous landing on a runway equipped with ultrasound transponders. To measure the airspeed we developed a hot wire anemometer that we thought would be better suited for low speeds than a pitot tube. When we built a calibration wind tunnel for the airspeed sensors, we discovered that the performance of differential pressure sensors at low airspeeds isn't so bad after all. A pressure sensor is used to provide barometric height computation. Telemetric data and control signals are exchanged over a 433 MHz half duplex radio channel. RPM gauge for the engine speed and battery monitoring provide additional information. The complete independence from a ground based camera system gives the airplane more mobility but increases the weight and requires a very high accuracy of the inertial navigation system.

In the current setup the inertial navigation system, the transceiver and the sensor unit are on individual circuit boards, each equipped with a 40 MHz, 16 bit Infineon XC164 micro-controller, and connected by a CAN fieldbus. The distributed system allows individual development of each subsystem, well suited to bachelor and master theses projects. Integrating all tasks onto one controller could save board space and weight by eliminating duplicate hardware such as the processors, power supplies and other peripherals. A single processor with a higher clock rate could easily handle the necessary computation without the need of a network for data exchange. That however might result in a more complex software structure to enable several team members to develop separately for the same hardware. Due to the amount of calculations and the necessary accuracy, picking a processor with integrated hardware floating point unit would be a good choice for the next hardware redesign.

An important aspect of the project is that all hardware was developed by students at our university. Although prefabricated modules are commercially available, designing them in-house provides a wide range of advantages that outweigh longer development time and involved problems. It opens the opportunity to exactly match the requirements of the own project, especially weight considerations, allows to use brand-new sensors at lower prices than comparable modules and gives students insight into various fields of expertise. Nevertheless the complexity shouldn't be neglected. Reverse engineering a transceiver unit took more than one attempt to obtain a module that was comparable with the original one. Without a fair knowledge of high frequency engineering we spent many hours trying to identify the flaws in the design. So there are occasions where complete modules might be the better choice. But the more difficult it is to get a board up and running, the greater the joy is when it finally works.

V. SIMULATION AND CONTROL DESIGN

To accurately model, simulate and control an aircraft system is a key factor in all aerial robotic projects. Since small sized UAV's follow the same physical laws as full-scale planes, the fundamental theory of flight mechanics as presented in aviation textbooks [6] is also applicable but it makes sense to simplify these models. Especially choosing a simple airframe configuration and restricting the flight envelope to simple manoeuvres allows various simplifications. The overall mathematical description of an UAV can be divided into an aerodynamic model, a propulsion model and a mechanical model including center of gravity and mass distribution. While the aerodynamic parts include static, dynamic and control characteristics the propulsion part models the static and dynamic thrust forces and moments caused by the engine and the propeller. There are several different ways to perform system identification of an UAV to obtain coefficients for the mathematical model.

While parameter identification from real flight test data requires advanced filter methods to estimate coefficients another approach has been established in the field of UAV development called the Digital Datcom method [10]. Digital Datcom is a software tool released for public, allowing an accurate prediction of almost all aerodynamic coefficients by defined vehicle geometry and an expected flight envelope. In our case, Digital Datcom has shown satisfying results for our small sized fix wing UAV. Since Datcom parameter estimation is independent from a flyable aircraft, it can be used concurrently to hardware and software development allowing parts of the team to simulate the dynamics and design control laws without having a flyable prototype available. A similar approach to Datcom is available for estimating propulsion, in particular propeller coefficients (JavaProp).

Having all parameters measured, estimated or assumed the model can be simulated within a mathematics software tool or a stand-alone executable program. In our case we choose the Matlab environment in conjunction with Simulink and the

Aerospace Toolbox to create a 6-degree-of-freedom nonlinear simulation, running in almost real time. As an alternative to the commercial Toolbox the AeroSim Blockset is available for free, given that it is used for education only [7]. This Blockset contains a variety of predefined aeronautical functions like coordinate transformations or calculations of forces and moments.

Having an accurate model of the plant allows to design the control laws. It is important to define levels of autonomy at the beginning and start with the low-level controller (e.g. control of angular rates or angles) followed by mid- and high-level controllers or autopilot state machines. It is obviously that flight control tasks have a wide bandwidth leading from simple stabilization and damping up to fully autonomous functionality. Since the aerodynamic model of the vehicle is a MIMO system utilizing the state space representation makes sense. But for educational use it is also sufficient to consider the aerodynamic model to be decoupled from longitudinal and latitudinal movements and flown at a constant pace. Assuming this simplifications leads to a SISO plant dynamic where linear control theory is applicable [8][11] (e.g. the elevator to pitch angle transfer function can be simplified as a 2nd order system). In our case this approach was chosen for a group of students who designed an angular controller for hovering flight in an embedded control course.

Before our first autonomous flight attempts, we thought of a construction like a mobile (see Figure 3, the airplane is vertical at hover tests) to hang the airplane up onto strings to roughly identify the aerodynamic properties for hover flight mode. It turned out that the mount was not appropriate for that matter because it introduced additional momentum into the system and was much to unstable.

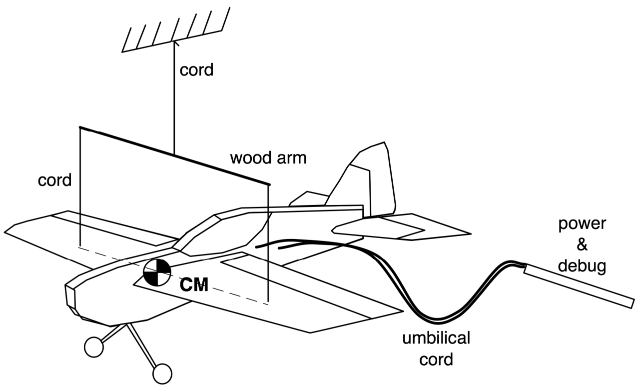

Figure 3. Mounting construction for a system identification attempt.

Another approach to identify simplified dynamics for hovering, that hasn't been tested, is to mount the aircraft with the centre of gravity on a ball head, a so called gimbal mount (see Figure 4). That kind of mounting represents a limited 3-degree of freedom platform which can be used to measure impulse or step responses initiated by the control surfaces.

An even better approach as already mentioned is system identification by data obtained from real, manually controlled flight experiments. That way information can be collected under almost the same conditions like in an autonomous flight. Unfortunately only a small amount of the recorded measurements are suitable for system identification purposes. In our case this method is still in progress and we are looking forward to get our first system models ready for simulation at the beginning of the next study year.

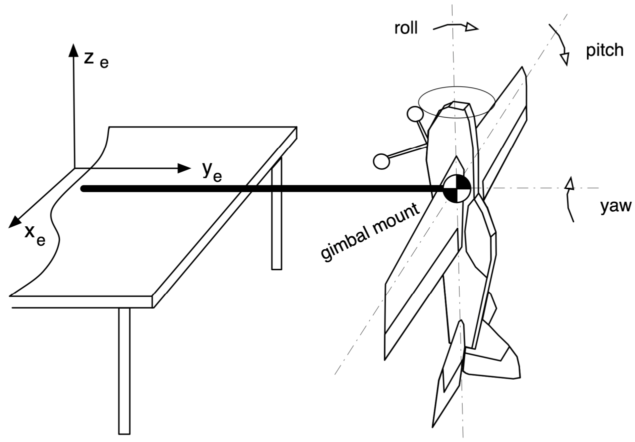

Figure 4. Gimbal Mount construction for a system identification attempt.

For the system identification based on the recorded flight data we use the Matlab System Identification Toolbox. Notice that in our case all flight controllers, sensor systems and actuator systems are designed, modeled, checked and evaluated within the Matlab/Simulink simulation environment.

Figure 5. FlightGear Screenshot [7].

There are many ways to visualize simulation results. While scopes can be used easily and fast to display scalar time responses, Matlab/Simulink is also able to visualize simulation results in an Open Source flight simulator called FlightGear[9]. It can be used as a stand alone flight simulator or it is remote controlled by network interface with the simulation results from the Matlab environment. See Figure 5 for a screenshot.

Within our project a simpler 3D animation window was designed, displaying our current vehicle's geometry as shown in Figure 6.

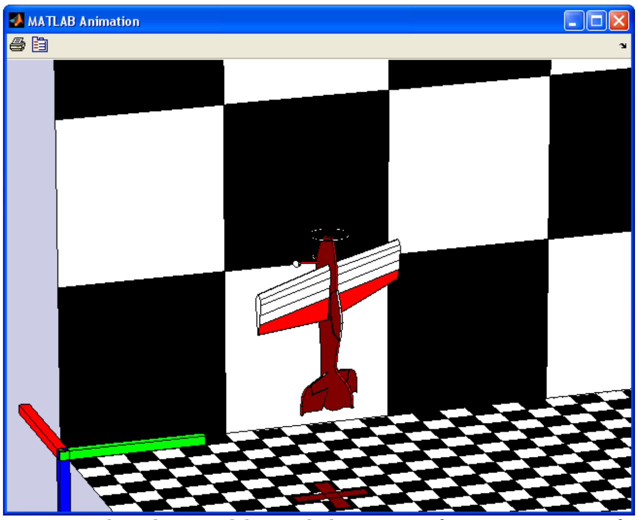

Figure 6. Adapted 3D Matlab/Simulink animation for our current aircraft.

VI. Conclusion

For the UAV team members the UAV-project is a great, challenging opportunity to demonstrate most of their acquired skills within their bachelor and master theses projects. Many of them work for the first time in a one year lasting project. From the point of view of a professor it is very satisfying to do this introduction to project life with such a beautiful project setup including so different interacting disciplines like sensorics, electronics, telemetry, control engineering, software design, state of the art simulation and most of all real world, high agility flying machines.

When teaching some of the project topics in classroom courses, care must be taken that the presented problems are not too complex, that the initial training effort is low and that the course materials are well prepared. With a careful introduction to the quite complex theories behind UAV flight there is a good chance to inspire the students to dig deeper in this topic. Using functional models to perceive the concepts will help a lot.

Looking back at our last year airplane we have to improve a lot. It is much to heavy, too fast and therefore too dangerous. Also the wing profile is not optimal and will be changed to a delta wing configuration. We need also more and simpler airplanes from the beginning on. The same is to say for the avionic board. We will change from a modular concept, although it had some advantages, to a hopefully less weight, single board concept with only one MCU that in turn is more powerful. With our Matlab/Simulink/FlightGear simulation environment we are really happy. The tools are mighty and the documentation is comprehensive. We look forward to the next year of fascinating work on UAV's.

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