

Automatic Control Project Course: a positioning and control application for an unmanned aerial vehicle

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ABSTRACT: In the *Conceive – Design – Implement - Operate* (CDIO) project course in automatic control, an autonomous unmanned aerial vehicle (UAV) is constructed, utilising an existing radio controlled model aircraft. By adding an inertial sensor that measures acceleration and rotation, together with a Global Positioning System (GPS) sensor, the aim is to construct an accurate positioning system. This is used by an onboard computer to calculate control surface signals to a set of servos in order to follow a predefined way-point trajectory. The project involves 17 students and comprises both positioning, control and hardware design. The main pedagogical goal is for students to apply their theoretical knowledge within a project framework in order to improve important aspects of their engineering skills in a realistic manner.

INTRODUCTION

The Applied Physics and Electrical Engineering (Y) programme at Linköping University in Linköping, Sweden, has participated in the *Conceive – Design – Implement – Operate* (CDIO) Initiative since the second half of 2000. A summary of the results is presented in ref. [1]. One of the main results is that a set of project courses has been introduced in the fourth year of the programme. In this article, one of the projects from the *Automatic Control* project course is presented. A further example of similar character is discussed in ref. [2].

The CDIO project in Automatic Control for last year MSc students in applied physics and electrical engineering at Linköping University has been implemented in cooperation with industry. Various projects have been pursued in groups of about six to eight people, with new project tasks each year. During spring 2006, a new approach was tested where a relatively large group (17 students) was involved in a more extensive project.

The main task in the project is to control and navigate a small radio-controlled aircraft using a very small Global Positioning System (GPS) unit. Hence, accurate position and velocity measurements are available (about 2-5 m position error), but only twice a second. In order to support the positioning system, an inertial measurement unit (IMU) with accelerometers, gyros and magnetometers (compass) is used. This sensor gives data at a much higher data rate (100-400 Hz) and also the rotation (angular velocity) of the aircraft can be measured. Hence, by combining these sensors (sensor fusion), a performance gain can be achieved. The estimated state (position, velocity and orientation) is utilised in the control part, which aims at following a previously defined trajectory or path. In order to achieve this, control signals to electrically controlled servos for the control surfaces are generated from a single board ARM Linux computer and some developed electronic circuits [1].

The project comprises issues such as safety and robustness, project management, state-of-the-art estimation (fusion) techniques, real-time computations, electronic circuit design, software development and system integration. However, the main pedagogical goal is for students to apply their theoretical and technical knowledge within the framework of a project in order to improve their engineering skills.

In this article, the authors discuss CDIO-specific topics, the drawbacks and benefits of a large sized project, learning outcomes and the technical achievements.

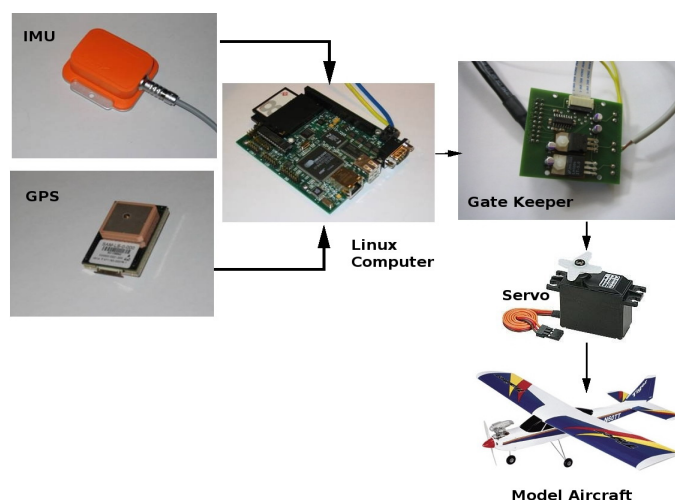


Figure 1: System overview. The system uses the Xsens IMU and a u-blox GPS, for positioning [3][4]. The algorithms are implemented on the Linux embedded ARM TS-7200 computer where also the control algorithms are implemented [5]. The control signals are fed to a small ATmega16 processor, which commands the servos to the correct position using the developed *gatekeeper* module [6]. All this hardware is located inside the model aircraft.

The project course in Automatic Control is a 200-hour course where groups of at least six students undertake projects according to the locally developed project management model called Linköping Interactive Project Steering (LIPS) [7]. In the 2006 course, there are seven projects, as follows:

- The positioning and control of an unmanned aerial vehicle (Dept. of EE);
- The diagnosis of a combustion engine (Dept. of EE);
- The modelling, simulation and optimisation of vehicle traction (Dept. of EE);
- Collision avoidance (Saab Bofors Dynamics);
- Micro EFIS (DST Control);
- Positioning with Bluetooth (Saab Aerotech);
- Autonomous underwater vehicle (Saab Bofors Underwater Systems).

As can be seen from this list, three projects are carried out at the EE Department, while four are carried out in cooperation with companies. This year, 65 students participated in the course. The first project is described in detail below. Seventeen students participated in this project. The size of this group is about three times the size of a normal group. The preliminary findings on what impact this has on the end result, both with respect to technical outcome, as well as regarding student experience, are also discussed in the sequel.

COURSE ORGANISATION

The course starts with a presentation of all available projects. Students then choose which project they would like to carry out. Based on students' choices, the examiner of the course assigns students to the different projects.

For each project, there is a customer, sponsor, project manager and a supervisor. For industrial projects, the customer is a person at the company, while for internal projects, the customer is a faculty member from the Department. The sponsor is a graduate student and the task of the sponsor is to be the link between the customer and the project group. The role of the supervisor, who, in most cases, is a graduate student, is to support the group with technical knowledge. The project manager is one of the students in the project group.

At the beginning of the course, students write a requirement specification, which is then approved by the sponsor together with the customer. The end product is later evaluated against the requirement specification. If there are requirements that the group cannot meet, those requirements have to be renegotiated with the sponsor and the customer.

Formal meetings between the sponsor and the project group have to take place at decision points before the group enters a new phase of the project. At a decision point, the sponsor reviews the progress of the project and decides if the project is allowed to move into the next phase. Minutes from these meetings are utilised by the examiner as inputs for the students' final assessment.

Within the groups, each student gets his/her own area of responsibility. In addition to the project manager task, the areas of responsibilities are documents, quality, testing, customer relations and technical design. The project manager should report weekly to the sponsor on how the project is developing.

In this section, the autonomous unmanned aerial vehicle (UAV) project is described in detail. The project can naturally be divided into three sub-projects involving sensor fusion techniques for positioning, control and guidance techniques, and hardware/electronic parts. Instead of running three separate small projects, a more realistic industrial-like project is formed by incorporating all these parts in a single project, as follows:

- Positioning;
- Control;
- Hardware.

The project and some of its major parts are depicted in Figure 1. The aircraft contains two navigation sensors, one GPS sensor and one IMU sensor [3][4]. These will send position, velocity, acceleration and rotational (angular velocity) information to the onboard ARM TS-7200 Linux computer [5]. Here, positioning and control algorithms will filter the data and calculate the control signals. These control signals are then sent to the servos using hardware developed for the project. Also, crucial to all the algorithms is a good and accurate model of the aircraft. This model is derived by physically modelling and identifying parameters using experiments or in simulations. Also, visualisation is an important task in the overall project as it enables evaluation of test-flight performance. This is carried out in the FlightGear tool, depicted to the left of Figure 2.

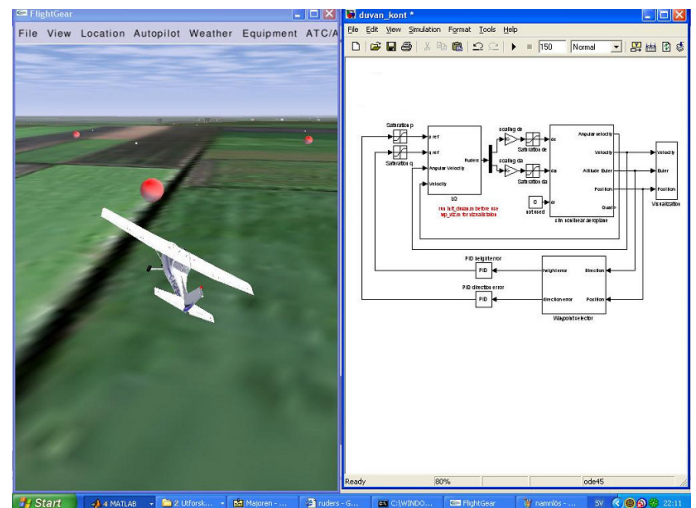


Figure 2: The visualisation tool for the simulation and flight evaluation with highlighted waypoints and the *Matlab Simulink* control design overview.

Positioning

The positioning group is mainly responsible for sensor fusion. The IMU sensor consists of an accelerometer that measures acceleration, a gyro that measures the angular velocity (rotation) and an electric compass. The acceleration vector can be integrated twice in order to obtain a position. Similarly, the rotation can be integrated from simple mechanical relations, yielding the aircraft orientation. This is achieved by implementing an extended Kalman filter (EKF) [8]. This technique of integrating sensor data that has small bias and drift terms will eventually lead to divergence or erroneous estimates. By incorporating absolute position and velocity values from the GPS, this can be handled in the EKF framework. Also, the compass can be incorporated in order to minimise these problems.

The filter will also need an accurate aircraft model, which mainly is provided by the control group. It is fed with input signals from the control surfaces in order to accurately estimate the states, for instance position, velocity and orientation. Another important topic for the positioning group is the correct initial alignment of the IMU.

Control

The control group is mainly responsible for building an accurate model of the aircraft. This is undertaken by physically modelling and identifying the parameters using measurement data or simulations. This model is used both for control, positioning, and in simulations and visualisation. The control task consists of both the guidance part, ie following a reference trajectory, and the fast control loop of the plane. The actual control of the rudders is carried out by the actuators in the form of servos, which take input or control signals from a designed electronic board, consisting of an ATmega16 processor [6]. The control law for the aircraft is based on a linear quadratic Gaussian (LQG) regulator [9]. The navigation component, ie the waypoint regulator, is mainly based on simple PID controllers for reference generation. The visualisation tool (FlightGear) and the *Simulink* control structure are depicted in Figure 2.

Hardware

The hardware group is mainly responsible for the onboard computer and all electrical design, as well as the communication related software. The core part is the embedded ARM TS-7200 Linux-based computer [5]. Since it is running a dedicated Linux kernel, it is easy to develop executable code using a C cross-compiler (based on GCC [10]) on a normal desktop computer. An external computer can easily communicate with the TS-7200, for instance using TCP/IP over an Ethernet cable.

The main task for the hardware group is data collection, for example from the IMU and GPS. This is achieved by interfacing these over a serial protocol. The hardware group is also responsible for the data collection and control signal generation in the *gatekeeper* module (see Figure 3). The actual signals to the servos are given by an ATmega16 processor [6]. Everything is then implemented on a specially designed circuit board.

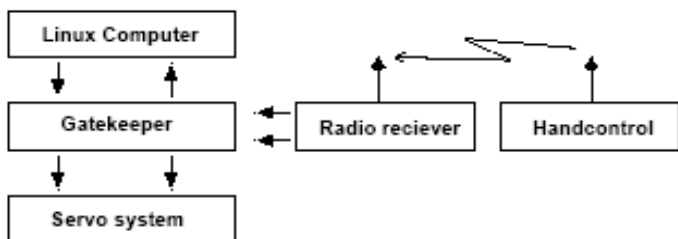


Figure 3: The *gatekeeper* module, dedicated for communication between the servos based around an ATmega16 processor and the TS-7200 Linux based computer. The *gatekeeper* module is used both for control and data collection.

PROJECT HIGHLIGHTS

In this section, several of the different phases in the project are highlighted. Also discussed are some of the experiences gained and problems that occurred.

Definition Phase

Before the project started, a sort of risk reduction phase was conducted by the sponsor and the customer. Mainly, all hardware (IMU, GPS and Linux computer) and communication between them were tested. Also, a small circuit was designed and built for easy communication and interfacing with the GPS signal and for voltage regulation.

When students were assigned to the project, it was decided that they should form three sub-projects in positioning, control and hardware. From these groups, work started on selecting the different roles for the project members. A project/group leader for each sub-project was also selected. These project leaders are responsible for managing the entire project together.

The project began with a long definition phase, where specifications for the various sub-systems were made. All this resulted in a project specification with testable requirements.

Execution Phase

After the definition phase, the actual work began. During this time, theoretical work was carried out by studying various parts needed for the project, for instance flight mechanics, estimation theory and system identification. Mathematical models were designed, filters tested and hardware constructed. All these elements had to be ready for a first flight test after about 12 weeks of work. From this flight-test, the model should be identified and various sub-systems tested.

Several test-flights were conducted with the model aircraft. During the first two, only GPS data and IMU data collection were tested. Since autonomy was not tested, this was easily carried out in the neighbourhood at a small airfield close to the University.

Both of these initial tests were successful and a lot of important experience was gained for the ongoing project, as well as for the hardware group, in order to make the electrical control module ready for rudder data collection and control.

The final test-flight was originally intended to be autonomous. During the last couple of weeks of the project, it became clear that more time was needed for a safe and robust autonomy. Hence, the final test-flight was only a proof of concept, where measurement data was collected, but the actual automatic control of the aircraft was not connected. The project group estimated that approximately two more weeks for some persons are needed to finalise the entire project.

Delivery Phase

A final meeting was held at the delivery where all of the different groups presented their projects. The examiner checked that all project goals and time schedules were fulfilled. The project delivered a fully functional, aircraft-based, measurement platform, which, with small adjustments, permitted its autonomous operation. In addition to that, simulation models and a visualisation tool were delivered.

After the project, a mandatory evaluation phase was carried out in order to collect and reflect upon the experiences from the project, both from a technical and a project management viewpoint.

DISCUSSION AND CONCLUSIONS

The major difference compared to other ongoing projects and from all the University's previous projects is the size. The challenge of managing 17 students instead of about six to seven was the key issue that gave the project the complexity of a quite large sub-system in any industry project. It was also clear that the size of the project really led to more project management issues and that the normal communication problems that occur during a project were more visible.

The size of the project also made it possible to have several complex tasks, in this case positioning, control and hardware design. This led to a more complex and fun project, which made it hard or impossible for only one or two students to conduct the project by themselves. Instead, everyone had to rely on the project management, fellow team members' work and the support of all involved supporting people.

This also encouraged the use of the LIPS project model probably more so than for smaller projects. The size of the project also made it possible to motivate buying some of the expensive equipment that was needed, such as the IMU, the radio controlled aircraft and the onboard computer.

The main drawback with a big project is that there will be more issues that are not directly related to system design and technical work. The project managers will spend a lot of time working with non-technical issues and administrative matters. However, this is probably an important issue in real projects and one issue that the CDIO framework can provide good training in.

Within the project framework, it is believed that the learning outcomes, the project goals and the following aspects are tested on the students in order to improve their engineering skills.

Conceive:

- A deeper understanding of fundamental signal processing and control theory in practice;
- The ability to break down a big and complex task into sub-problems with sufficiently measurable demands;
- The overall project management and project work, which consists of planning, time schedules and dealing with limited resources.

Design:

- Small simulation environments with components crucial for the sub-systems, such as control laws and positioning filters, were designed and tuned in order to be prepared to handle measurement data;
- The *gatekeeper* module, responsible for signals control and data collection, was developed.

Implement:

- Data collection task using manufactured hardware;
- Coding in order to implement the various sub-systems in the real-time onboard system;
- Visualisation tools were implemented or modified in order to be able to analyse data from the test flights.

Operate:

- The size of the project really motivated students to run the project according to a project model;
- It gave some support to meet sub-system specifications to allow for interaction between the sub-projects;
- An accurate test and verification phase are crucial.

To summarise, most of the project goals were completely or partially fulfilled within the project. The main reason that the entire project could not perform full autonomy in a test-flight was the lack of sufficient tests and verifications of the interacting sub-systems. Also, the ability to identify critical phases within the project in an early stage and to direct more resources was one factor that did cost a lot of time, for instance, a fully functional *gatekeeper* module early in the project should have been prioritised. To address similar issues, programme evaluation and review technique (PERT) charts will be utilised in future projects. However, the project has been opened up for further work on positioning and control problems, where all the sub-parts can be reused. Most importantly, the project tested and improved students' engineering skills in a realistic manner utilising a large project with demanding technical goals, which was the main pedagogical goal.

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