POSITIONING AND CONTROL OF AN UNMANNED AERIAL VEHICLE

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ABSTRACT

In the CDIO-project course in Automatic Control, an *autonomous unmanned aerial vehicle* (UAV) is constructed, utilizing an existing radio controlled model aircraft. By adding an inertial sensor measuring 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 on board computer to calculate rudder control signals to a set of DC-servos in order to follow a predefined way-point trajectory. The project involves 17 students, which is roughly three times as big as previous projects, and it comprises both positioning, control, and hardware design. Since the project is still ongoing some preliminary results and conclusions are presented.

1 INTRODUCTION

The CDIO (*Conceive, Design, Implement, Operate*) project in Automatic Control for last year M.Sc. students in Applied Physics and Electrical Engineering at Linköping university, Sweden, is implemented in cooperation with industry. Various projects have been pursued in groups of about $6 - 8$ people. During the spring 2006 a new approach is tested where a relatively large group (17 students) is 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 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, orientation) is used in the control part which aims at following a previously defined trajectory or path. To do so, control signals to electrically controlled DC-servos for the rudders are generated from a single board ARM Linux computer, [4], and some developed electronic circuits. The project comprises issues as: safety and robustness issues, project management, state-of-the-art estimation (fusion) techniques together with real-time constraints, electronic circuit design, and software development.

The paper will discuss CDIO specific topics, drawbacks and benefits of a large size project, and the technical achievements. The project runs from January 16 to May 19, 2006. The paper is organized as follows: In Section 2 the background of CDIO initiative is briefly discussed. In

Section 3 the CDIO Automatic Control project course, [5], is described in general. In Section 4 the autonomous *unmanned aerial vehicle* (UAV) project is discussed in detail. Finally, in Section 5 conclusions are given.

2 THE CDIO INITIATIVE

In this section the CDIO initiative is described. In for instance [7] this is stated as:

> *CDIO is an innovative educational framework for producing the next generation of engineers. It provides students with an education stressing engineering fundamentals set in the context of Conceiving – Designing – Implementing – Operating real-world systems and products.*

The CDIO project is a cooperation between several universities, [7], for instance: Chalmers (Gothenburg, Sweden), Linköping University (Linköping, Sweden), Queen's University (Belfast, Northern Ireland), U.S. Naval Academy (Maryland, USA), KTH (Stockholm, Sweden), MIT (Boston, USA), and Technical University of Denmark (Lyngby, Denmark).

The background for the CDIO initiative is described on the CDIO-web page, [7]. In the beginning of 2000 a group of universities and technical institutes (Linköping, Chalmers, KTH, and MIT) applied for and was granted financing from the Knut and Alice Wallenberg foundation. This in order to start a common project to reform and reshape the teaching in engineering courses in the USA and Europe.

How a project should be conducted within the CDIO framework is described in [12] (downloadable from [7]). In that document it is stated that modern engineers must not only gain expert knowledge in engineering subjects, they must also be able to express themselves in speech and writing, as well as interacting with team workers in order to fulfill the overall project goal. In [12] it is also described how the engineering subject is taught in academia and how that differs from what is used in industry. This is also described in [9]. Before *World War II* (WWII), there appeared to be more balance between teaching and what was applied in industry. Also the teachers had more experience from industry and the focus was on problem solving. This often lead to a greater understanding of the theory thought. After WWII the technical knowledge increased dramatically, which lead to less practical and more theoretical education. When this was realized it led to a need for reforming the engineering education. Now focusing on integration of theory and practice using the key words: *Conceive, Design, Implement, and Operate* (CDIO). In [12] it is clearly stated that many leading managers in industry supported this change on the universities and technical institutes.

In the document CDIO-Syllabus, [12], skills that are needed are defined, such as

> *Graduating engineers should be able to conceive-design-implement-operate complex value-added engineering systems in a modern team-based environment.*

Even though the CDIO initiative is quite recent, there is already a lot written, for instance reports, conference papers etc. A large collection of these are available on-line from [7]. These are within a wide range of subjects. In [6], a reflection of the CDIO-program is made: how participating universities interact, and information gained after a year, and some future plans. In [9] different projects within universities and technical institutes are described, with the main attention to the project course in the first year. In [8], the education of technical education and CDIO are studied for Linköping university (Electrical Engineering and Applied Physics), Chalmers (Mechanical Engineering), KTH (Aeronautical and Vehicle Engineering), and MIT (Aero Astro).

3 THE CDIO AUTOMATIC CONTROL PROJECT COURSE

In this section the CDIO-project course in Automatic Control, [5], is presented. To be able to efficiently apply a CDIO project course a project model is often used. This is discussed by briefly introducing the locally developed project model, LIPS.

3.1 OVERALL DESCRIPTION

The CDIO-project course in Automatic Control is a 200 hours course where groups of at least six students do projects according to the LIPS project model. Quoting the official course plan, the aim is:

> "The project should be conducted according to industrial standards and it should develop the students competence in the following areas: - How to analyze engineering problems - Research of knowledge - Application of knowledge obtained from previous courses - To find creative solutions - When applicable, the project work should consist of modeling, design, implementation and testing of a control system."

In the course of 2006 there are seven projects:

1. **Positioning and control of an unmanned aerial vehicle** (Dept. of EE)

2. Diagnosis of combustion engine (Dept. of EE)

3. Modeling, simulation and optimization of vehicle traction (Dept. of EE)

4. Collision avoidance (Saab Bofors Dynamics)

5. Micro EFIS (DST Control)

6. Positioning with Bluetooth (Saab Aerotech)

7. Autonomous underwater vehicle (Saab Bofors Underwater Systems)

As can be seen from this list, three projects are carried out at the EE department, and four are carried out in cooperation with companies. This year 65 students participated in the course. In Section 4, the first project is described in detail. In this project 17 of the students participated. The size of this group is about three times the size of a normal group. Our preliminary findings on what impact this has on the end result, both with respect to technical outcome as well as with respect to student experience, will also be discussed in the sequel.

3.2 COURSE ORGANIZATION

The course starts with a presentation of all available projects. The students then choose which project they would like to carry out. Based on the 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 the industrial projects the customer is a person at the company, and for the internal project 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, the 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 re-negotiated 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 in the LIPS project model. 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 used by the examiner as inputs for the final assessment of the students.

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 how the project develops.

3.3 OVERALL GOALS

In this section some of the goals with the CDIO-project course in Automatic Control are given. The participants are supposed to practice, exercise, and improve their skills in various different areas exemplified below:

- *Conceive:*

  - Understand basic theory
  - Divide the main task into sub problems
  - Planning (time schedule and resources)
  - Formulate measurable demands and specifications

- *Design:*

  - Design a complex product
  - Simulation

- *Implement:*

  - Hardware implementation
  - Sensor data collection

- Operate:

  - Project management and project work
  - Get various sub-systems to interact correctly
  - Meet the project specifications
  - Tests and verifications

It is worth noticing that even if the project aims at an autonomous UAV, many of the goals with a "student project" are not directly related to a successful product. Instead the main focus is actually on practicing various important tasks within the project framework.

Another goal with this years course was also to focus more on project management and the actual project model. To be able to do this, a large project, consisting of three different sub-projects was formulated. The idea was that this larger project would be more realistic and the need for management and project structure would be more obvious.
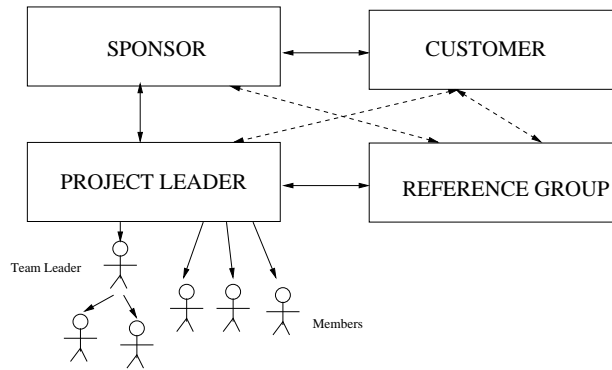
Figure 1: Organization in a typical university project according to the LIPS model.

3.4 THE PROJECT MODEL (LIPS)

The LIPS project model[1], [11], contains instructions, and templates to manage a project. It is specially developed for student projects or small industrial projects. The idea behind the model is scalability, i.e., be applicable to a diverse variety of projects, for instance Master's Theses, university projects or projects in cooperation with industry. Basically, LIPS contains three phases: the *definition phase* with preparation and planning, the *execution phase*, and the *delivery phase* with finalization and evaluation. The model also contains detailed description of different roles, such as project leader, customer relations responsible, documentation responsible etc.

In Figure 1 an example of the organization for a project in a typical university or student project is depicted. For a student project the sponsor is an employee at the university, with a responsibility for the overall project work. The customer is either an external customer if it is an industry project, or an employee at the university if it is an internal project. The reference group gives technical support and expertise for particular subjects. They are mainly supported by the university, but for industry projects, also technical expertise from the involved company is included in the group. Usually several formal or informal ways of communicating are present in a project, as depicted in the figure.

The organization and detailed descriptions of the different parts, tasks and responsibilities are described in detail in [11]. Different phases; divided in before, under, and after the project are thoroughly described. The responsibilities for different persons or task are for instance as: documentation, testing, quality control, customer relations etc. The CDIO-projects in Linköping follow this project model from [11] as much as possible, or the recommendations given in it. Therefore, it is often not distinguished between CDIO-project management or the LIPS model in practice.

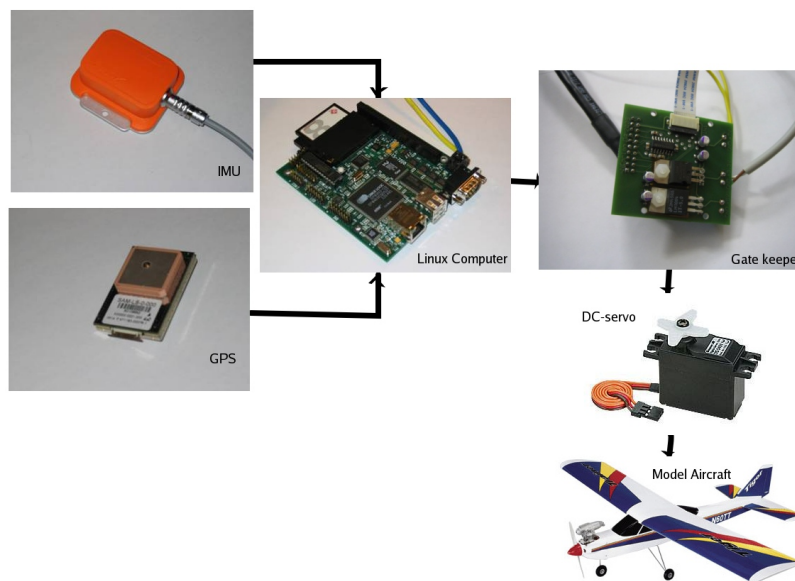[1]Swedish: Lätt Interaktiv Projekt Styrning

Figure 2: The UAV system overview. The system uses the Xsens IMU, [2] and a u-blox GPS, [1] for positioning. The algorithms are implemented on the Linux embedded ARM TS-7200 computer, [4], where also the control algorithms are implemented. The control signals are fed to a small ATmega16 processor, [3], that will command the DC-servos to the correct position. All this hardware is located inside the model aircraft.

4   THE AUTONOMOUS UAV PROJECT

In this section the autonomous UAV project will be 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:

- Positioning

- Control

- Hardware

In Figure 2, the project and some of its major parts are depicted. The aircraft contains two navigation sensors, one GPS-sensor, [1], and one IMU-sensor, [2]. These will send position, velocity, acceleration, and rotational (angular velocity) information to the onboard ARM TS-7200 Linux computer, [4]. Here, positioning and control algorithms will filter the data, and calculate rudder control signals. These control signals are sent to the DC-servos using some hardware developed for the project. Also, crucial to all the algorithms is a good and accurate

Figure 3: The visualization tool for the simulation and flight evaluation with highlighted way-points and the MATLAB Simulink control design overview.

model of the aircraft. This model is derived by physical modeling and identification of parameters using experiments, or in simulations. Also visualization is an important task in the overall project as it enables evaluation of test-flight performance. This is done in the *FlightGear* tool.

As mentioned, the CDIO-project course in Linköping is always carried out in accordance with a locally developed project organization model for CDIO-project, the so-called LIPS organization model, see Section 3.4. To fit the current project we decided to have one project leader for each sub-project. But to minimize overhead and allow the students to be able to participate in the technical work, it was decided not to have one general project leader for the entire project. Instead the three project leaders will form a steering-committee, the three members responsible for documentation will form a document group and so on.

4.1   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. Similar, the rotation can from simple mechanical relations, be integrated, yielding the aircraft orientation. This is done by implementing an *extended Kalman filter* (EKF), [10]. 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 minimize these problems. The filter will also need an accurate aircraft model, which mainly is provided by the control group. It is feed with input signals from the rudders, in order to accurately estimate the states, i.e., for instance position, velocity, and orientation. In order to have a robust implementation the orientation of the aircraft is expressed using quaternions.

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Another important topic for the positioning group is correct initial alignment of the IMU.

4.2 CONTROL

The control group is mainly responsible for building an accurate model of the aircraft. This is done by physical modeling and possibly identification of parameters using measurement data or simulations. This model is used both for control, positioning and in simulations and visualization. The control task consists of both the guidance part, i.e., follow a reference trajectory and the fast control loop of the plane. The actual control of the rudders is done by the actuators in form of DC-servos, which take input or control signals from a designed electronic board, consisting of an ATmega16 processor, [3]. The control law for the aircraft is based on a LQG-regulator. The navigation part, i.e., the way-point regulator, is mainly based on simple PID-controllers for reference generation. The visualization tool (FlightGear) and the Simulink control structure are depicted in Figure 3.

4.3 HARDWARE

The hardware group is mainly responsible for the onboard computer and all electrical design, and communication related software. The core part is the embedded ARM TS-7200 Linux based computer, [4]. Since it is running a dedicated Linux kernel, it is easy to develop executable code using a C cross-compiler (based on GCC) 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 instance from the IMU and GPS. This is done by interfacing these over a serial protocol. The hardware group is also responsible for the data collection and control signal generation in the "gate keeper" module, see Figure 5. The actual signals to the DC-servos are given by an ATmega16 processor, [3]. Everything is implemented on a specially designed circuit board.

4.4 PROJECT HIGHLIGHTS

In this section several of the different phases in the project are highlighted. Also some experiences gained and problems that occurred are briefly discussed. In Figure 4 the model aircraft is depicted before and under one of the test-flights.

DEFINITION PHASE (LIPS)

Pre-project work: 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 of the GPS signal, and for voltage regulation.

Project member assignments: When the 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 different roles for the project members. Also a project/group leader for each sub-project was selected. These project leaders are also responsible for managing the entire project together.

Definition and specifications: The project started with a long definition phase, where specifications for various sub-systems were made. All this resulting in a project specification with testable requirements.

Figure 4: A collection of pictures from the project. Upper Left: assembling the model aircraft electronics and sensor equipment. Upper Right: During one of the test-flights. Lower Left: Pre-flight calibration and initialization. Lower Right: The model aircraft.

EXECUTION PHASE (LIPS)

Project work: After the definition phase, the actual work began. During this time, theoretical work was done 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 things 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-system tested.

Initial test-flights: Several test-flights were conducted with the model aircraft. During the first two, only GPS data and IMU data collection was tested. Since autonomy was not tested, this was easily done in the neighborhood at a small air-field close to the university. Both these initial tests were successful and a lot of important experience was gained for the on-going project, and for the hardware group in order to make the electrical control module ready for rudder data collection and control.

Final test-flight: The final test-flight was originally intended to be autonomous. During the last couple of week 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 were measurement data was collected, but the actual automatic control of the aircraft was dis-engaged. The project group estimated that approximately two more weeks for some persons are needed to finalize the entire project. This will probably be done in a Master Thesis project or part of a future UAV-project.
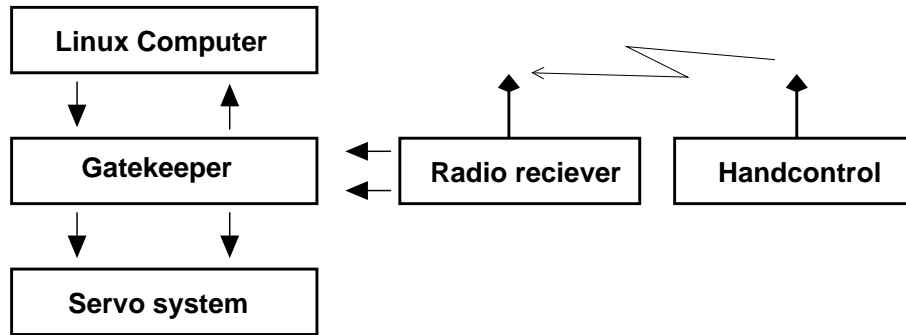
Figure 5: The "gate keeper" module, dedicated for communication between the DC-servos based around an ATmega16 processor and the TS-7200 Linux based computer. The "gate keeper" module is used both for control and data collection.

DELIVERY PHASE (LIPS)

Project result: A final meeting will be held at the delivery, where all different CDIO-projects will meet and demonstrate their projects. It is then time for the examiner to check that all project goals and time schedules are fulfilled. The project will deliver a fully functional, aircraft based, measurement platform, that with small adjustments will allow for autonomous operation.

Project evaluation: After the project a mandatory evaluation phase will be carried out.

5 CONCLUSIONS

In this section a summary and conclusions are given. Since the project is still ongoing, and no evaluation has been done yet, only preliminary technical results are given.

The major difference compared to other ongoing projects and from all our previous CDIO projects is the size. The challenge of managing 17 students instead of about $6 - 7$ 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 lead 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 lead 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, team member work, and the support of all involved supporting people. This also motivated the project model LIPS, probably more than for a smaller project. The size of the project also made it possible to motivate buying some expensive equipment 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.

In Section 3.3, several goals with a CDIO-project course was formulated. In the UAV-project we believe that the following aspects are tested within the project framework:

- *Conceive:* A deeper understanding for some 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. Also the overall project management and project work, which consists of planning, time schedules and limited resources.

- *Design:* By building small simulation environments, 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. Also, the "gate keeper" module, responsible for rudder signal control and data collection, was developed.

- *Implement:* The data collection task, as well as hardware realization were two important implementation aspects. As well as all coding in order to implement the various sub-systems in the onboard system. Also, visualization tools were implemented or modified in order to be able to analyze flight-test data.

- *Operate:* The size of the project really motivated work according to a project model, in this case LIPS. It also gave some support to meet sub-system specifications to allow for interaction between the sub-projects. Crucial is also an accurate test and verification phase.

Summarizing: most of the project goals from Section 3.3 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 there was one factor that did cost a lot of time. To address this issue, pert charts will be used in future projects. However, the project has opened up for further work on positioning and control problems, in for instance a Master's Thesis project, which can be based around a fully functional measurement platform. Or in extension to the project for future projects within the CDIO-framework. It was roughly estimated that the initial project goal could have been reached with about two more weeks of work for some of the key members.

ACKNOWLEDGMENT

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