2006-2134: A MULTI-DISCIPLINARY SENIOR DESIGN PROJECT USING COOPERATIVE UNMANNED AERIAL VEHICLES (UAVS)

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A Multi-Disciplinary Senior Design Project Using Cooperative Unmanned Aerial Vehicles

1. Abstract

To improve our response to U.S. Air Force requirements, the Department of Electrical and Computer Engineering at the U.S. Air Force Academy has integrated multidisciplinary team projects into its two-semester capstone design course. In this paper we present a case study of one of our multidisciplinary projects for the 2005-2006 academic year; developing a system of cooperative unmanned aerial vehicles (UAVs). Some of our instructional methods include just-in-time teaching, team faculty mentoring, and requiring timely scheduled oral and written reports, to name a few. The goal of the project is to have three UAVs cooperatively seek, detect, and monitor a ground target. The students come from the academic disciplines of electrical engineering, computer engineering, and systems engineering management. To be successful, the team must use a system engineering approach to (1) manage the project development process, (2) implement onboard controllers and an automatic tracking ground station and (3) test and evaluate the final product, all while adhering to a team-developed schedule. The final product must meet requirements of sensor remote control, sensor data downlink, communication, embedded computing, and minimum flight duration. We show that our techniques improved the overall quality of the students' learning experience.

2. Introduction/Background

In response to evolving U.S. Air Force requirements, the five departments that make up the Engineering Division at the U.S. Air Force Academy have shifted their emphasis from individual projects to multidisciplinary team projects for their senior-level, two-semester capstone design courses. Design teams consist of students from a variety of engineering disciplines and, in some instances, a student majoring in systems engineering management. The roles of the different students on each project team reflect their disciplines. This approach has been providing our students with real world engineering experiences. These experiences include, in addition to the traditional engineering design activities, learning to work with other students from outside their own discipline, establishing and adhering to an integrated team project timeline, identifying and managing risks, generating periodic progress reports and briefings, and creating and executing a test plan.

During the 2005-2006 academic year, the Department of Electrical and Computer Engineering has been overseeing eight capstone design projects. The projects involve 30 students majoring in electrical engineering, computer engineering, systems engineering, general engineering, and systems engineering management. Table 1 shows a listing of this year's projects and the make up of the student teams. A faculty mentor is assigned to each team to guide and direct the student team throughout the academic year. A volunteer senior faculty member serves as the team's "customer" and provides feedback at all formal reviews and status briefings. In addition to these two faculty members, the faculty course administrator participates in and assesses all formal reviews and reports. The faculty team mentors the students on both the technical and program management aspects of the project.

Project	Description	Students Involved
Formula SAE Car Electronics	Develop, integrate and test an engine control, electronic gear shift, and telemetry system for the USAFA Society of Automotive Engineers Formula competition vehicle. The USAFA Formula SAE car will compete with entries from 140 other colleges and universities in 2006 for honors at the SAE Formula Competition.	3 Electrical Engineering 1 Computer Engineering
Full Sky Digital Camera	Develop system to monitor the night sky incorporating a high *f*-number fish eye lens and a high sensitivity large area CCD array which is swept through the lens' field of view under computer control. Images obtained from this camera will then be interlaced in mosaic form to form an image of the entire night sky.	3 Electrical Engineering 1 Computer Engineering 1 General Engineering
Infrared Camera Control	Design, develop and implement a custom control sub-system for a state-of-the-art infrared camera. This camera is capable of gathering hyper-spectral data through which the image and time resolved spectra content of an optical event can be recorded and analyzed.	2 Electrical Engineering
Sound Pressure Level Monitor	Develop and install a Sound Pressure Level (SPL) Monitoring system in the dormitories of the USAFA Preparatory School. The equipment must continuously record SPL data, store a time record of the data, and, when commanded, produce average SPL data over specified time intervals.	1 Electrical Engineering 1 Computer Engineering
UAV GPS Navigation	Evaluate, re-design, develop, upgrade, integrate and test the Autonomous Model A/C Flight Control System. Cadet engineers will expand the capabilities of a previous flight-control system (FCS) to include a Global Positioning System receiver. The updated FCS will be capable of guiding the model aircraft to a maximum of 10 pre-programmed GPS coordinates.	2 Electrical Engineering 1 Computer Engineering 1 System Engineering
Controlling Multiple UAVs	Demonstrate hardware and software technologies to control multiple UAVs to search, detect, and monitor ground targets.	3 Electrical Engineering 2 Computer Engineering 1 System Engineering Management
Hovering Robot	Develop an autonomous hovering robot to demonstrate the feasibility of creating such robots for reconnaissance missions.	2 Electrical Engineering 1 Computer Engineering 1 System Engineering
Ultrasonic Sonar System	Design an ultrasonic sonar system for use in the Electrical Engineer 434 Digital Signal Processing (DSP) course to allow the students to collect and process live sonar data and teach them the basic principles of RADAR.	2 Electrical Engineering 1 Computer Engineering
	Total Students	**30**

Table 1: Senior Design Projects for 2005-2006

This paper addresses the requirements of the project, the systems engineering concepts introduced to the students in the course, the development of the team, the learning opportunities provided, and techniques used to influence team performance and dynamics in the context of the cooperative multiple UAVs project.

3. Project Description

The goal of the multiple cooperative UAVs team is to design and develop a three UAV system to search for, detect, and monitor ground targets. The three UAVs are to fly with video camera sensors and communicate telemetry and video data to an air tracking control station (ATCS) via an air-to-air/air-to-ground communications network. Each UAV shall be autonomous, meaning it will fly and maneuver on its own without continuous input from a ground controller. The airborne electronic resources must weigh less than the aircraft load limit of 8 pounds and be powered for not less than 20 minutes operation. Each UAV needs to communicate with two other UAVs in the network as well as with a ground station. Each UAV's on-board video camera pointing angle shall be controllable in three axes by an operator on the ground.

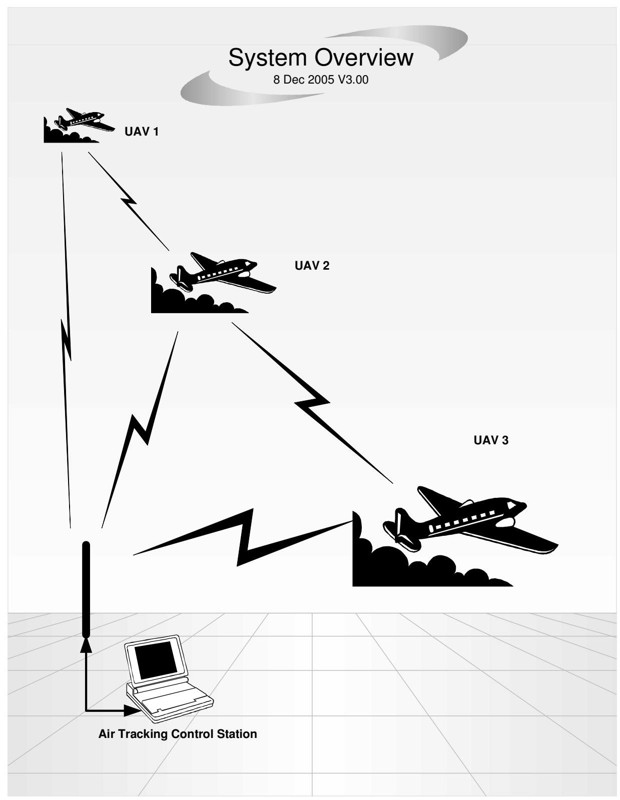

Figure 1 – System Overview [4]

Figure 1 shows an overview of the cooperative UAV system. The three UAVs are commercial-off-the-shelf (COTS) radio-controlled aircraft whose radio control is not shown in Figure 1. The student-designed system operates in the following manner.

The onboard electronics for a single UAV is illustrated in Figure 2. While flying at 300 ft above ground level, the onboard camera, mounted on a three-axis gimbal system, is used to search for a 10 ft × 10 ft white target on the ground. The camera is controlled by an operator via the ATCS. Control signals for the camera will be sent through the ad-hoc wireless network from the ATCS to the UAV. This wireless network also delivers telemetry data and video from the UAV to the ATCS. When a UAV is too far from the ATCS to receive its signal, data will be routed through other UAVs. The COTS Piccolo, manufactured by Cloud Cap Technologies, performs flight control either in the manual control or autonomous mode, gathers telemetry data, and makes it available to the JREX onboard processor. The JREX adds a time stamp and a UAV identification number and assembles the video and telemetry data into packets to be sent over the network.

The ad-hoc network consists of the three UAVs and the ATCS. Each node has a Proxima 802.11b wireless card and an antenna that allows the UAVs to be 500 meters apart and still communicate with all other nodes in the network.

The ATCS displays simultaneously the video and telemetry data from three aircraft on its monitor, and also allows a user to adjust the orientation of the camera on any particular UAV.

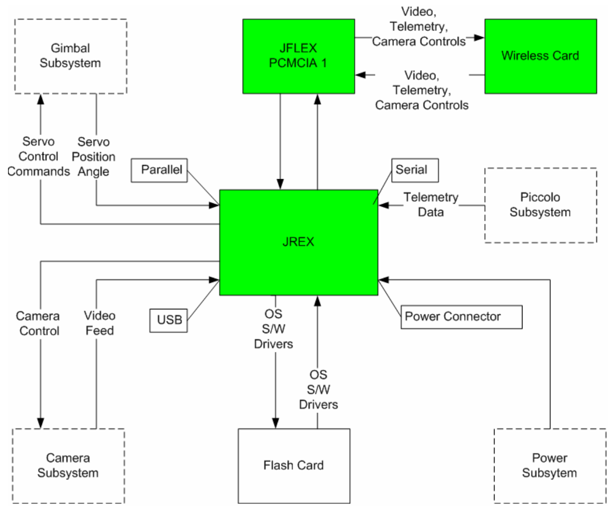

Figure 2 – UAV System Top-Level Block Diagram [4]

4. Project Programmatic Requirements

At the beginning of the fall semester, the student team is given the project assignment which contains the performance requirements for the UAV system, a budget, and mandatory schedule milestones. The team must design, build, and test a final product that meets the performance requirements while developing reports and presentations in accordance with the milestone schedule shown in Table 2.

The two-semester course requires a systematic system engineering process similar to the product development process in use in the Air Force and industry. In the first semester, the cadets focus on requirements definition, project planning, and design execution of the engineering project. Students receive instruction on project management tools and methods, analysis of requirements, software and hardware design specifications, quality assurance, and testing.[1] During the spring semester, emphasis is placed on development of hardware and software, testing and evaluation, quality assurance, and documentation[2].

31 Aug 2005	System Requirements Review
23 Sep 2005	Initial Design Review
26 Oct 2005	Preliminary (High Level) Design Review
17 Nov 2005	First Draft of Test Plan due
28 Nov 2005	First Draft of Technical Report due
8 Dec 2005	Critical (Detailed) Design Review, Updated Schedule
14 Feb 2006	Second Draft of Technical Report and Test Plan due
15 Feb 2006	First Project Status Review
15 Mar 2006	Second Project Status Review
12 Apr 2006	Third Draft of Technical Report and Final Test Plan due
10 May 2006	System Verification Review and Final Technical Report due

Table 2: **Academic Year 2005-2006 Schedule**[1,2]

The student team has a variety of system engineering issues it must address to complete the course: requirements analysis, software and hardware design, a test and integration plan, periodic reports, and briefings. The team must also address cost, risk identification and mitigation, reliability, manufacturability, and maintainability. In addition, the team must consider potential project impacts relating to ethics, health, safety, society, and environment. Lastly, the team must develop and maintain a website to keep mentors and customers apprised of their progress.[2]

5. Project Status

At the time of this writing, the team has designed and developed all the subsystems and is in the process of integrating and testing the overall system. In this section we briefly discuss the status of the project.

Figure 3 shows the graphical user interface developed for the ATCS. Note that the three screens on top of the interface show images seen by the three UAVs, the bottom left map shows the locations of the three UAVs, and the lower right hand sub-window shows the telemetry data. Figure 4 shows the airframe for a single UAV.

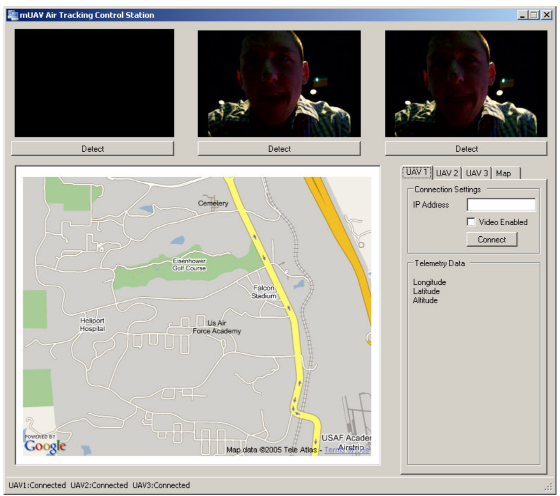

Figure 3 – Graphical User Interface for ATCS [4]

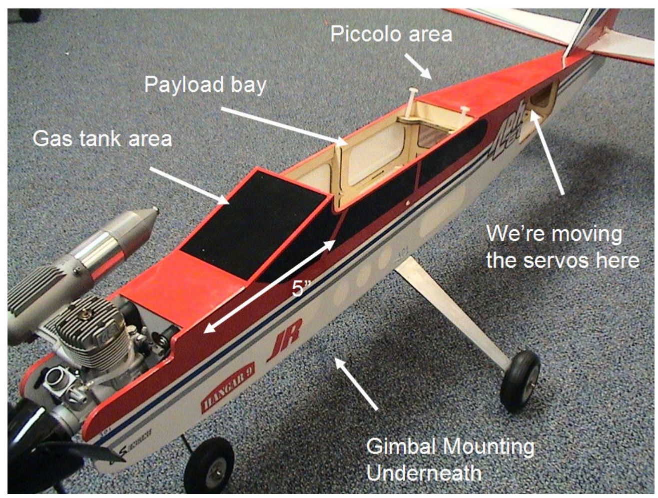

Figure 4 – Hardware Layout [4]

The team has demonstrated delivery of telemetry data to the JREX and subsequently to the ATCS. The camera system and associated software has provided a video streaming feed to the ATCS. The team has also been able to control the camera using operator inputs routed through the ATCS to the JREX.

6. Evaluation of Learning Experiences and Lessons Learned

In this section we evaluate the techniques used to (1) administer the interdisciplinary cooperative UAV project, (2) help students learn system engineering knowledge and skills using the project, and (3) enable students to manage their team dynamics. We also briefly present some important lessons we learned from administering the project and observing challenges the students faced.

The student team was formed before the fall semester started based on the stated desires of the students and the faculty-determined needs of the project. We identified one SEM student who works as the team project manager, two computer engineering students who are responsible for the bulk of software development on the ATCS and the JREX board, and three electrical engineering students who work on the communication system, the power system, the user interface system, and the sensor platform control system. All students perform integration, test, and analysis tasks for the project. A definite challenge for the faculty mentor of a multi-student team is to ensure that all students accept approximately equal responsibilities for planning, engineering, test, and documentation tasks. An additional challenge with multi-disciplinary teams is to divide the work along disciplinary lines. Generally, we have found the bigger challenge is to ensure equality of effort. The better students often become so enthused that they tend to pick up work with which the poorer students may be struggling. This area offers the mentor the opportunity to ensure the students learn how to work on inter-disciplinary teams and assist, not replace the weaker team members.

To support the UAV student team, we also put together a team of five faculty mentors with expertise in system engineering, communications, integrated circuits, embedded computer systems, and software development. We were lucky in this regard as the USAF Academy has a very active, interdisciplinary UAV Research Group (UAVRG) and members of the group were willing to devote the required four to ten hours a month as mentors to this project. In addition to their two assigned mentors, other projects rely on faculty experts within the department in software design, signal processing, electromagnetics, etc., who answer well-posed questions from the students when required. In addition, through the UAVRG, we have access to technicians and radio-controlled aircraft pilots who will help the students during the final stage of the project as they assemble and fly the UAVs. We understand that a typical university may not be able to form a faculty and support team such as the one described. However, we strongly believe such a support team model should be followed to the extent practical for students to fully experience and benefit from a complex senior capstone design project such as the multiple cooperative UAVs system.

The fall semester of the course was previously roughly divided into two phases. During the first phase, the engineering students learned practical hardware implementation techniques and system engineering concepts and skills such as the use of Microsoft® Project to plan and schedule project activities. During the second half of the semester the students completed system requirements analysis and multiple iterations of software and hardware designs. This year we implemented just-in-time (JIT) learning, so the lessons on system engineering were taught at the beginning of the fall semester and three hardware implementation lessons (mainly covering the proper use of COTS modules such as analog-to-digital converters, voltage regulators, power supplies, etc. and available laboratory resources) came during the detailed design phase. This JIT technique worked very well as the immediacy of the need for the knowledge provided additional motivation for the students and retention was much better as evidenced by the improved designs and system engineering products produced by the students.

To ensure the students learn the importance of identifying and clarifying system requirements, we intentionally introduced ambiguity to initiate discussion and clarification among the student team members and faculty. In this project and several others listed in Table 1, we found that these discussions served not only to clarify the engineering problem in the students' minds; but to bring about changes to the requirements as the faculty better understood the impact of certain specifications. Up to and during the System Requirements Review (SRR), clarifications and changes were encouraged when appropriate. However, after the SRR, changes were allowed only when clearly justified by the faculty or students using an impact analysis. Indeed, we found that the addition of system engineering management (SEM) and system engineering (SE) majors to selected student teams resulted in much better control and documentation of the requirements. Nearly all projects used a Requirements Traceability Matrix implemented in Microsoft®Excel to document and manage requirements.

During the design phases, students performed trade studies to select hardware components for their final designs. For the cooperative UAV project, trade studies were conducted on batteries, antennas, on-board video cameras, and servo motors. The department puts significant emphasis on the consideration of alternatives so most teams produced complete, well-reasoned trade studies. Those teams with an SEM or SE assigned produced slightly better documentation for their trade studies. This year continued an innovation introduced last year, the addition of a formal Initial Design Review about half-way through the high-level design phase. This formal briefing is intended to provide more practice in organizing and presenting design status, ensure more interaction between faculty and student teams, and help keep the students on schedule. We have found that the students' confidence in their abilities often led them to delay their design effort for too long and resulted in incomplete designs. Adding the Initial Design Review did produce the intended positive effect on the student preliminary designs.

Along with the formal briefings, bi-weekly informal status meetings provide students and faculty with an interactive learning environment to determine whether or not the student team is focusing on the proper processes and making appropriate progress. We are still falling short of our goal of having very short meetings with the student-developed Microsoft®Project schedule being used to show project status. Any specific issues that arise would then be taken up between the team members or the selected team member(s) and the faculty mentor. Lack of experience seems to make it very hard for students to plan complicated projects with several team members. We have successfully used senior faculty with AF and industrial project management experience to facilitate the construction of initial schedules; but haven't completely solved the challenge of students using very detailed schedules to track and report progress on a weekly or bi-weekly basis. We intend to provide more learning opportunities including practice with Microsoft®Project next year in our system engineering courses taken by both the SEs and SEMs.

At appropriate times (see Table 1); the student team is required to turn in partial drafts of an integrated test plan and a comprehensive technical report. We have found that developing a test and integration plan takes multiple iterations with faculty feedback. Students usually lack the experience to know what sort of tests to run, what data to collect, and how to verify that subsystems are functioning properly. Furthermore they have problems determining a proper integration sequence and appropriate integration tests. The faculty team provides feedback for each submission in the form of detailed comments and grades. One lesson learned last fall was that *timely* feedback by the faculty was required to maintain student motivation. Consequently, we have set a standard that faculty feedback must be provided within four academic days (two lessons for us.)

In the spring semester, cadets previously have been engaged in detailed design; implementation; verification by analysis, testing, or demonstration; and documentation of their project. With the implementation of JIT learning last fall, the detailed designs were scheduled to be complete by the end of the fall semester. This was possible since additional time was made available by moving lessons on designing and implementing printed circuit boards to the spring semester. However, preliminary feedback from the faculty mentors suggests there still was not enough time for the students to complete their detailed design. In over one-half of the projects listed in Table 1, there were significant pieces of design missing as we started the spring semester. This issue will be addressed fully as the department completes its assessment process at the end of this semester.

Additional drafts of the test plan and technical report are submitted for faculty feedback and the final versions are completed during the spring semester (Table 1). The final test plan due date was intended to be before any subsystem testing started As the student teams developed their schedules, it became apparent the due date for the Integrated Test Plan should be tied to the individual project schedules developed by the student teams. As an integrated plan, the test plan includes both plans and procedures for subsystem testing as well as integration and system tests. The initially planned date of April 12 is too late in most student schedules for subsystem and the beginning of integration testing. Consequently, several mentors have required an earlier due date consistent with their particular team's schedule. This issue also will be reviewed during the course assessment at the end of the semester.

Instead of the bi-weekly meetings scheduled during the first semester, the UAV team meets with faculty once a week during the spring semester. Other teams, with fewer members, have found that bi-weekly meetings are sufficient. Weekly meetings provide an increased number of opportunities to ensure the students coordinate among themselves and receive timely guidance from the faculty team. The meetings have provided the mentor team with ample opportunities to provide feedback to the student team. As mentioned above, we are still trying to develop a useful, efficient format for these meetings that is suitable for the student experience level and the academic environment.

The mentor team has influenced the student team dynamics using a number of different techniques. First, we rotate the technical leadership of the student team among the engineering students throughout the two semesters to provide each student with technical leadership experience and the opportunity to observe how the team dynamics changes as the leadership changes. To maintain continuity for the UAV project, the student majoring in system engineering management remains as the project manager/coordinator performing the system engineering management tasks and ensuring close liaison between the student and faculty teams. On other teams the SE, general engineer, or a self-selected electrical or computer engineer performs the SEM functions, or they are shared. Secondly, the student team decided among themselves each student's responsibility for a subsystem of the project. A faculty mentor was then paired with each student. This one-on-one mentor/student time helps the mentor team to accurately gauge the team dynamics and provides the mentor team an opportunity to discuss any known problems with student team individuals. Third, the mentor team periodically has one-on-one meetings with all the students and takes appropriate actions if necessary. Finally, by encouraging communications among student team members in the form of regular informal meetings, we try to offer ample opportunities for team dynamics to develop.

One of most valuable lessons the student team is learning is how to deal with delays. Some of the delays are caused by manufacturing times for components. Others are caused by problems getting devices to work properly or to interface with one another. The team members are constantly revising their schedule to accommodate these delays so they are seeing the importance of having a detailed schedule that allows them to see the impact of each schedule slip.

7. Conclusion

In this paper we presented our experience mentoring a multidisciplinary student team working on a complex system of three cooperating UAVs. We described the use of just-in-time teaching techniques, a disciplined system engineering approach, and faculty team mentoring. At the time of this writing, the student team is in the process of implementing the software and hardware designs developed in the first semester. We are collecting data to validate the effectiveness of the techniques used during the second semester and will present the results at the conference.

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