AC 2011-187: MULTI-DISCIPLINARY CAPSTONE DESIGN PROJECT:
AN UNMANNED AIRCRAFT SYSTEM (UAS) FOR VEHICLE TRACKING

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Abstract

Over the past several years we have used a variety of unmanned aerial vehicles (UAVs) applications as multidisciplinary capstone design projects. In this paper, we present one of those projects in which the goal of the UAS is to search, detect, and identify an approaching vehicle, then relay the identity of the vehicle to a ground station in an environment with radio frequency (RF) interferences. The project team had seven students from four different majors: System Engineering Management, System Engineering, Computer Engineering and Electrical Engineering. We show how the project met not only technical requirements, but also the course objectives of following the proper engineering design process. This paper includes the assessment methods used and lessons learned.

1. Introduction

All engineering majors at the US Air Force Academy complete a year-long, multidisciplinary design course. In addition to teaching cadets the proper engineering design process, the course provides cadets with opportunities to exercise their skills and knowledge obtained throughout their engineering programs. The team-based approach not only allows us to take on larger and more challenging projects, but also gives students the experience and management challenges of working effectively in a multidisciplinary team.

The use of UAVs for senior design projects is not new. The University of Sydney’s records indicate they were experimenting with remotely piloted aircraft as far back as 1939. By the 1990’s, improvement in technology converged making low-cost UAVs possible and UAV projects grew in popularity with a number of UAV competitions such as the International Aerial Robotics Competition which was kicked off in 1991. UAVs offer a wide range of possible capstone applications. Examples include remote sensing for agricultural crop yield estimation and weed detection; coastal surveillance; mapping hazards at a disaster site; designing UAV platforms that can transform from fixed wing configuration to vertical take-off and landing (VTOL); designing platforms to handle the UAV challenge of low Reynolds Numbers; and the miniaturization challenges of micro air vehicles (MAV). Similarly, there have been many capstone projects in other autonomous systems domains using ground, surface and underwater vehicles.

Since the early 1990’s, we have used unmanned systems for several capstone design projects. We started with autonomous ground robots, and expanded to fixed-wing and VTOL autonomous aircraft systems. Examples include using an autonomous UAV to search and detect airborne chemicals for hazardous materials (HAZMAT); mapping the spread and damage of pine beetles in a Ponderosa pine forest; protection of a harbor by detecting and intercepting rouge boats; and using four UAVs to cooperatively search, detect, and monitor a ground target. This paper discusses a recent project whose goal is to inform a remote substation of an approaching
vehicle using an autonomous UAV and presents the engineering process, assessment methods, and overall lessons learned.

2. Course Structure and Assessment

The overall objectives for our one-year capstone course are that a successful student shall be able to:

1. Apply proper hardware design methodologies with previously acquired engineering knowledge to assess requirements, evaluate alternative designs, develop valid ready-to-build design solutions, construct a risk-reduction prototype and plan to verify the design meets requirements.
2. Apply proper software design practices with previously acquired software experience to assess requirements, develop valid ready-to-code software designs, write code for the risk reduction prototype and plan to verify that the design meets requirements.
3. Use system engineering and management tools including schedules, risk management, configuration management, and progress reporting to complete the project design, risk reduction prototype and integration and test plan on-time.
4. Cooperatively work as a multi-disciplinary team to execute the project plan.
5. Successfully communicate the details of a project through written documents and oral presentations.
6. Demonstrate recognition of the need for, and an ability to engage in life-long learning.
7. Evaluate project impacts on contemporary engineering issues, especially those relevant to military engineers.

Throughout the various phases of the course, we quantitatively assess these seven objectives at predetermined points across all the various capstone projects to arrive at our overall assessment of the capstone course. These objectives not only focus on measuring success by assessing the completion of the technical requirements of a project, but also emphasize the use of the proper engineering design process. The textbook we use to teach the engineering process is *Design for Electrical and Computer Engineers*, by Ford and Coulston, and follows procedures often used in industry.

The students derive and develop system requirements and designs during the first semester, and build, integrate, and test systems during the second semester. The milestones for the first semester include a Systems Requirements Review (SRR), a Preliminary Design Review (PDR), and a Critical Design Review (CDR). By the end of the first semester, a team should have a complete design and a risk reduction prototype of a key part of the system. In addition, the students complete several writing assignments documenting the different phases of the system and subsystem designs. Students present the SRR, PDR, and CDR to an audience including a technical mentor, the course director, a Senior Reviewing Official (SRO), and customers, who all assess the team’s performance. The course director tries to ensure fair grading across the capstone teams in the course. A SRO represents a general officer or corporate president. Example items from the CDR grading rubric include technical tasks such as requirements traceability, hardware system and subsystem designs, software design, integration plan, test plans, risk reduction prototype, weight budget, power budget, and programmatic tasks such as
schedule, risk management, configuration management, and cost budget. We also require the students to address contemporary issues such as safety, ethics, social, political and environmental issues.

If a team completes the first semester successfully, the project’s requirements and design should be well defined such that the team can immediately begin implementing the design during the second semester. The milestones of the second semester include two Program Status Reviews (PSRs), a System Verification Review (SVR), and a final project demonstration. The goal of the first PSR is to assess whether or not all subsystems have been successfully built and tested. By the time the second PSR is scheduled, teams should have integrated all subsystems and completed higher level tests. At the SVR the team completes an in-house review to show the system meets all the requirements. Finally, for this project the team performed a capabilities demonstration of the system in an operational environment for the project sponsors.

Figure 1. Mission Scenario

3. Project Scenario

The primary goal of the project was to inform a remote substation of an approaching vehicle using an autonomous UAV. The UAV system must search for a vehicle, detect it, and communicate to a ground station the identity of the vehicle. The UAV must do this in the presence of RF interference. Figure 1 shows an overview of the mission scenario. A human on the ground detects a designated vehicle and relays the information to the UAV ground station, where the UAV is launched to search for the vehicle. The UAV searches for the vehicle, detects it, and transmits it’s identify to a nearby remote ground substation as the vehicle approaches.

The design team was made up of one Systems Engineering Management (SEM) cadet, one Systems Engineering cadet, one Computer Engineering cadet, and five Electrical Engineering cadets. The SEM cadet took the role of Project Manager. The project scaled well as each engineer could be made responsible for his own subsystem.
4. Design Challenges

The first task for the team was to decide the best airframe to meet the mission requirements. We provide the students with several fixed-wing airframes to choose from. They chose the Kadet Senior R/C airframe\textsuperscript{12} shown in Figure 2. With its 78 inch wingspan, it can carry about 6 pound payload and cruise at about 20 meters/second for approximately 25 minutes.

![Figure 2. Picture of UAV in Flight](image)

Then the team had to design or integrate the following subsystems: (1) an onboard computer system that makes autonomous control, sensing, and communication decisions; (2) an autopilot system; (3) a ground station capable of monitoring the UAV mission; (4) a communication system, including a special antenna system to avoid the RF interference generated by the approaching vehicle (5) an onboard sensor (camera) system; (6) a backup manual RC control system; (7) an onboard power supply system; and (8) the remote ground substation. Figure 3 shows the overall system block diagram.

![Figure 3. System Block Diagram.](image)
For the single board computer, the team chose a Textron motherboard with a Pentium-4 level processor, primarily for its ease of use. Microsoft’s .NET framework was used as a virtual machine to easily integrate the code together as shown in Figure 4. This allowed the engineer in charge of the image processing software to use the MATLAB toolset he was familiar with, and still meet the real-time processing requirements. The team chose an open-source autopilot and properly interfaced it within the .NET environment. The aeronautic flight parameters used by the autopilot had to be mapped to those of our UAV to ensure stability.

![Figure 4. Software Environment](image)

Another engineer developed the ground station software and user interface, as shown in Figure 5. The ground station needed to present the real-time telemetry status and the global map with trajectories of the UAV to the user. In this figure the ellipse represents the UAV’s staging orbit and the red tracks represent the search path defined by the ground station operator.

![Figure 5. Ground Station User Interface](image)
The communications engineer selected 802.11g wireless (2.4 GHz) protocol between the UAV and the ground station and a proprietary 2.4 GHz radio to communicate with the remote ground substation. All communication channels were required to work within a 2 km range. To address the requirement to overcome the RF interference signal transmitted by the vehicle with at least 10dB SNR, the communications engineer first studied the vehicle’s antenna system. The vehicle used a dipole antenna, so he designed the communication propagation patterns between the UAV and the remote substation to be orthogonally polarized to the interference signal. The team outfitted the UAV with an omnidirectional half-wave dipole antenna and the remote ground substation with a helical antenna. The students initially verified that 10dB SNR could be maintained by performing tests in an anechoic chamber, and then verified the results in an outside field test at the maximum communication range required.

For the design of the camera system, the team had to study the requirements of the scenario carefully to select an appropriate camera. For simplicity they chose a fixed (versus gimbaled) color camera called the AXIS 212 Pan Tilt Zoom (PTZ) with a field of view of 140 degrees and 640x480 resolution. To simplify the image processing the customer allowed the target vehicle to be limited to a bright red car driving down a predefined road, as shown in Figure 7. The system reliably detected this target, however, in the final analysis, the team considered the image processing algorithm to be the weakest link to making a robust system.

A backup RC controller is necessary for takeoff /landings of UAVs and for safety backup control during the autonomous flight. We provided the team with a standard RC controller, thus it was not a design issue. The cadets did have to rigorously go through the Air Force flight safety rules for our airspace and prove their system met the safety standards to fly.

Power and weight budgets drove many of the tradeoff studies during the preliminary feasibility analysis phase as the team sought to ensure the UAV met the flight duration requirement. A power board was needed to provide proper regulated voltages throughout the system. Figure 6 shows the mounting of the various subsystems inside of and on the UAV fuselage.
The last subsystem the team designed was the remote substation. The remote substation had to receive target status from the UAV. It first received a signal when the vehicle was detected, then received updates as to the anticipated arrival time. The substation had its own sensor to detect the motion of passing cars to help correlate a proper passing car with the target being tracked by the UAV.

5. Results

The project met all technical requirements and the team successfully demonstrated the capabilities of the system to the customer. During the demonstrations, the car travelled at a low speed on a predefined road in a fairly straight line to simplify the task, as shown in Figure 7. The maximum range of 2 km was not exceeded and the communication was constantly maintained. The UAV successfully detected the car and transmitted the target status to the remote ground station in the presence of the 10dB RF interference signal. Figure 8 shows the ground station display of the UAV flight trajectories during the same experiment. The circular orbit on the top left corner shows the staging orbit of the UAV, the parallel paths on the right represent search paths of the UAV over the road, and the left bottom circular orbit shows the takeoff and landing trajectories of the UAV. We plan to show a demonstration video of the UAV performing the mission during our conference presentation.

In this project we successfully met the course goal of getting the students to follow our engineering design process and found the grades for the program management tasks were up from previous semesters. We feel this was primarily due to the addition of the SEM major. Our engineers seem to dread the program management and paperwork tasks. The SEM student greatly contributed by implementing good program management practices, teaching these methods to the engineers, and keeping the engineers on track with the schedule.

Across all our capstone projects, we assessed six of the seven course objectives (see section 2) as “green” or successful. The only “yellow” (marginal) objective was #7 concerning contemporary engineering issues. We found, while the students address these issues early in the course during the requirements definition phase, they tend to place little emphasis on them during the latter part of the course when they are mainly focused on getting their system to work.
6. Lesson Learned

   a. **Weak at program management.** Traditionally our engineering students were weak in managing programs, schedules, and maintaining documents. The addition of the SEM student to the team greatly helped with the program management tasks. Even with the SEM student, the team still found making a working schedule at the correct level of detail challenging. It was a constant battle to get the team to use the schedule as a tool rather than a paperwork exercise. Another concern we had with adding the SEM student was that the engineers may come to think that the management tasks (schedules, costs, etc) are only the job of SEMs, not engineers. We emphasize throughout the course that this is a key responsibility of all engineers in the “real world.”

   b. **Nail down requirements.** Defining the requirements and translating them to measurable technical specifications is usually the most challenging phase for our students. The teams that have had trouble completing their projects successfully are usually the ones that never get their requirements specified and committed in the first semester. Fortunately, this UAV team clearly defined the requirements early in the project.

   c. **Design first, then build.** Students naturally want to build as soon as possible, designing as they go (or afterwards). We spend the first semester holding them off from building and preaching to them to design first. The one exception to this is we require a risk reduction prototype. We found we have to watch the team closely as this prototype can be a slippery-slope towards trying to build the whole system. Some teams get wrapped up in the prototype and fail to complete their detailed design/analysis. The UAV team’s prototype focused on one key challenge. Their prototype demonstrated that they could communicate wirelessly at the system’s max range in the presence of the estimated RF noise, answering several questions needed to complete the detailed design.

   d. **Scaling project and team size.** The larger the team, the more challenging it is to find a project that scales to the team size, keeping the workload balanced, and holding every team member accountable. Accountability works the best when there is a well-defined subsystem for which each team member is responsible. When we have multiple team members working on one subsystem we often find that either one person does all the work or it is difficult to assign academic credit to individuals. This UAS team project was fairly well balanced with each person being responsible for a subsystem; however, the optimum number may have been one less engineer.

   e. **UAV is a good platform for Capstone.** The cadets at the Air Force Academy tend to be highly motivated to work on UAV projects as they see its relevance to their future career and these projects are considered “cool.” Other authors as well have noted UAVs make motivational projects. In addition, full-size conventional aircraft are too expensive and above the scale for our capstone projects. On the other hand, RC
class plane size UAVs we use are rather low cost, easy for our students to build and add subsystems to, and are easier to get permission to fly than large aircraft.

f. **Real Customers.** In the past only a few of our capstone projects had external customers. Now we typically have about 80% of the projects externally sponsored. Having an outside sponsor helps legitimatize the project in the eyes of students and usually raises their level of professionalism. Our team was ecstatic when the UAV worked successfully at the capabilities demonstration in front of the customer. But we’ve also found we have to be careful that the customer’s needs do not interfere with our pedagogical goals. We try to avoid the pressure that the product cannot fail which can stifle the creative process and not allow the students the learning opportunity as they make mistakes. We have learned to carefully manage the customer’s expectations before the project begins that there is a chance the product may not pass the desired project requirements at the end.

g. **Multiple Bosses.** At the end of the first semester, we often receive feedback that the students feel they have multiple bosses, often with contradictory guidance. The mentor says one thing and the customer wants another. We use this as a teaching point at the beginning of the second semester. We value this tension as it reflects real-world projects and makes the students take ownership of the requirements and gain consensus of all parties before pressing on to the next phase.

7. Conclusion

In this paper we discussed the capstone design course at the US Air Force Academy and presented an example UAV project. We find the UAV platform offers many challenges as a good capstone project and is motivational for our students. In addition students are more motivated when they have customers with real-world needs. The various subsystems of the UAV can span several disciplines from electrical and computer, to mechanical, to aeronautical, to human factors, making it a true multi-disciplinary project. UAV systems also have the advantage of enough complexity to warrant inclusion of a systems engineer or a systems engineering management major on the project team.

Bibliography


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