AN UNMANNED AERIAL VEHICLE PROJECT
FOR UNDERGRADUATES

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ABSTRACT

Brigham Young University recently introduced a project for undergraduates in which a miniature unmanned aerial vehicle system is constructed. The system is capable of autonomous flight, take-off, landing, and navigation through a planned path. In addition, through the use of video and telemetry collected by the vehicle, accurate geolocation of specified targets is performed. This paper outlines our approach and successes in facilitating this accomplishment at the undergraduate level.

KEYWORDS

uav, unmanned aerial vehicle, undergraduate education, geolocation, path planning

1 INTRODUCTION

Miniature Unmanned Aerial Vehicles (mUAVs) are becoming increasingly useful in both commercial and military applications such as area monitoring, fire tracking, and object geolocation. At Brigham Young University, the Multiple AGent Intelligent Coordination and Control (MAGICC) research lab has successfully developed a number of important mUAV technologies, including capabilities for autonomous navigation, multi-agent cooperation, vision guidance and control, and target geolocation algorithms. This technology has seen real-world use both in our lab and in commercial mUAV systems. Typically, however, only graduate students have the necessary technical background to actively participate in the field. At BYU we have developed a novel course for senior undergraduates which prepares them to contribute in this dynamic field.

In this paper we will first introduce the structure of the course, its associated labs, and infrastructure. We then describe some of the approaches taken by each of the design groups into which the students were partitioned, namely the path planning and guidance group, the vision system group, and the air-frame and autopilot design group. We also present the results of the final competition which showcase the students’ achievements. We then conclude the paper.
2 COURSE STRUCTURE

In this section we describe the structure of the course. In the sub-sections below, we outline the objectives for the course, how the students were organized, how the 15-week semester was utilized, and the infrastructure and instruction provided to the students.

2.1 Course Objectives
The course’s primary objective was for the students to produce a product with the following capabilities:

1. autonomous takeoff, landing, and flight
2. navigation through a designated area searching for targets while avoiding no-fly zones
3. geolocation and bombing (with small fishing weights) of targets

These objectives were designed to coincide with the Association for Unmanned Vehicle Systems International (AUVSI) competition [1]. BYU is sending a team of students selected from the course to this competition.

2.2 Organization of Students
In previous project-based courses, we have found that a combination of a team based environment and an atmosphere of friendly competition encourages students to perform better. To this end, the class was divided into 4 teams of 7 or 8 students. Sub-groups were created within each team, to work on different areas of the overall system. Specifically each team was divided into three sub-groups:

**Path Planning and Guidance Group** This group was responsible for developing algorithms and techniques for navigation of the mUAV. This includes strategies for planning an appropriate path (covering a search area, and avoiding no-fly zones), and following it.

**Vision System Group** This group was responsible for developing a vision based system capable of tracking a user-specified target, and accurately geolocating that target.

**Air-frame and Autopilot Group** This group was responsible for construction of the mUAV, as well as system integration and maintenance.

Each team had the responsibility of creating a fully functional final product. Beginning midway through the semester scheduled competitions were held which represented major milestones in the design process. We discuss the final competition and its results in Section 3.

2.3 Course Schedule
We divided the 15 weeks of the semester into five weeks of instruction/lab work and 10 weeks of team work and collaboration. In the first 5 weeks formal instruction and labs were used to familiarize students with necessary concepts. In the last 10 weeks students were given time to complete the project as a team and prepare for competitions. Design reviews were also held periodically throughout the semester to allow advisors to provide the various teams with feedback and guidance.
2.4 Design Reviews
During design reviews students were expected to make a thorough presentation of their progress, ideas, concepts, designs, future plans, and problems. Professional presentations were expected and the design reviews were graded accordingly.

Besides providing the benefit of allowing the advisors to know and understand each team’s progress, the reviews served as a way to encourage students to evaluate progress, identify problems, and plan solutions. This provides an important structure for helping students learn how to achieve objectives in a team setting.

2.5 Labs and Instruction
During the first five weeks of the semester, we held regular class instruction and labs. Separate lectures and labs were held for each of the three design groups. The lecture and lab sections for each design group were overseen by a professor specializing in each area. Teaching assistants for each main section were also available to assist the students as well as monitor labs, competitions, and other logistics.

Air-frame and Autopilot Labs: The labs for the Air-frame and Autopilot group were designed to help the students learn basic concepts for construction of the aircraft and implementation of the autopilot control. Topics included:

- construction of the airframe
- calibration of control surface servos
- remote control (RC) piloting as backup against system failure during flight
- programming the autopilot hardware
- running the hardware with flight simulation software
- writing and tuning Proportional Integrator Derivative (PID) feedback loops
- schemes for attitude estimation and lateral and longitudinal autopilot control

Path Planning and Guidance Labs: The labs for the Path Planning and Guidance group were designed to introduce students to general algorithms and concepts in path planning and following, and expose them to the hardware they would be using to implement such algorithms. Students were introduced to the Rapidly-exploring Random Tree (RRT) algorithm, as well as some modifications to this algorithm to handle area coverage while avoiding obstacles [2]. The labs included such tasks as waypoint following, search path planning and smoothing, obstacle avoidance, and testing in simulation.

Vision System Labs: The labs for the Vision System group helped students understand and implement the techniques which could be used to track and geolocate targets from video. These labs included camera calibration, rigid body transformations, and implementation of feature tracking methods [3][4].

2.6 Hardware and Software Tools
We provided a set of tools from third party software vendors, sponsors, and research at the university to help the students complete the project. To enable proper instruction for RC pilots, we
provided COTS flight simulator software called RealFlight G3. For system testing in simulation, students used an mUAV simulator called Aviones, previously developed by BYU’s Computer Science department. This software enabled the students to test vision, path plans, and control dynamics in simulation before actually flying.

The air-frame provided to the students was the Multiplex EasyStar [5] shown in Figure 1. This air-frame is ideal for novice pilots due to its in-flight stability. It has a wingspan of 54 in. with dihedral, length of 36 in., weight of 1.50 pounds, and two servos for individually controlling its rudder and elevator.

The autopilot used was Procerus Technologies’ Kestrel Autopilot 1.45 [6] shown in Figure 1. The Kestrel weighs under 40 grams, measures $2.86 \times 1.97 \times 0.58$ in., and contains a full suite of on-board sensors. Procerus’ Virtual Cockpit software was used at the ground station to command and communicate with the autopilot.

Video was captured on the mUAV and relayed back to the ground station by a Black Widow KX-141 [7] color CCD camera coupled with a 600 milliwatt Black Widow analog transmitter. This system provides $640 \times 480$ resolution interlaced video at a frame rate of 30 frames per second, and weighs less than 50 grams. The video is transmitted as an analog NTSC signal, which is captured and re-digitized at the ground station by an ImperX VCE-Pro FrameGrabber [8].

### 3 COURSE OUTCOMES

In this section we describe some of the algorithms developed by the students, and give some information about the performance achieved through the use of these algorithms. We then show the rules and results of the final competition.

#### 3.1 Path-planning and Guidance Group

The path planning and guidance group was responsible for developing algorithms to plan paths through designated search areas while avoiding no-fly zones. All teams used the RRT algorithm [2] in their path planning methods. The goal of this algorithm is to construct a tree that connects locations in the search space. This tree represents a collection of possible paths through the search
The algorithm begins with the starting location of the mUAV as the root vertex of the tree. It then randomly generates a new location within the search area using a random distribution. The vertex closest to this new location is selected, and a step of a fixed length is taken from this nearest vertex in the direction of the random location, thus adding a new vertex to the tree. If this newly added branch of the tree traverses a no-fly zone or other obstacle it is deleted from the tree. As the algorithm runs, multiple valid paths are generated. After sufficient time the valid paths are evaluated and the “best” path is selected.

Teams were able to use the RRT algorithm in different ways to achieve their specific objectives. One team used a distribution they designed which was weighted around the destination point, as shown in Figure 2. This introduced more direct paths through the region, but took longer if an obstacle was directly between the starting and ending points.

Another implementation started with an evenly spaced grid of locations to be visited throughout the area. All invalid (no-fly zone) locations were removed. The approach was to iteratively build a shortest path to cover all valid locations. This was done by using an RRT algorithm, with a uniform distribution, to generate all the paths between the current grid point and each remaining grid point at each step. The shortest path was then selected and added to the overall current path. This process was repeated until all grid locations had been visited. This algorithm’s strength was its ability to handle no-fly zones of any shape while still exhaustively searching the area and finding a good path. The algorithm, however, did not consider the turning radius of the aircraft and often generated paths that contained sharp turns that were infeasible for the aircraft.

This problem was addressed by a different team whose algorithm planned a spiral path outward from the middle of the area. In this algorithm, no-fly zones were addressed when the path intersected it. At that time the shortest distance around the no-fly zone was calculated using the RRT algorithm. This method, however, could not handle concave no-fly zones in a robust fashion.

3.2 Vision System Group
The goal for the vision system group was to design a system capable of searching an area for user-defined targets, and calculating GPS locations for those targets based on the visual data collected. Students were not given the target descriptions until one day prior to the competition. This required the students to design robust algorithms that do not need much \textit{a priori} information. As a result, all
teams chose a vision system that required a user in the loop to select targets during flight. Feature based tracking algorithms were then used to track the selected targets across multiple video frames. Given a target’s location in a group of frames, a least squares approach was used to find the GPS coordinates of the target.

Throughout the semester two different tracking systems were developed to dynamically select and track targets. Both systems included a user in the loop to click on desired targets in the video. Both were implemented using the Open Computer Vision Library (OpenCV) [9].

**System 1:** The first system solves the tracking problem by finding a homography matrix which maps every point in one image to the corresponding point in the next frame of the video. Once this homography matrix is known, determining the location of a target in the new frame reduces to a matrix multiply and two divides. This system assumes that the scene being photographed is planar [3] - a valid assumption when the mUAV flies high above the ground.

The advantage of this system lies in its capability to track targets through large camera displacements. On the other hand, there is some slipping of the tracking over time due to noise in the image and because the ground is not perfectly planar. The user was able compensate for this slippage by reselecting the target of interest during flight.

**System 2:** The second tracking system tracked the point of interest by taking a template block of pixels around the point and searching for that block directly in a region of the next frame. Such a search method relies on the assumption that the template block only shifts its position from frame to frame (i.e. there is no rotation or perspective distortion of the block). This assumption often does not hold. To address the failure of this assumption, this system performs a search for two template blocks in each image. The first template block is the original block of pixels centered around the user’s original click (i.e. several frames ago). The second template block is centered around the most recent feature location estimate (i.e. in the last frame). A best match location is found for each of these template blocks, and a statistical average (based on match quality) is used to combine these two locations to form the new feature location estimate.

This system has high resilience to image noise and camera jitter, and is able to re-capture a target that has been temporarily lost due to extreme camera movement. In order to run this system in real time, however, the search area for template blocks must be kept relatively small. This implies that template blocks cannot move very far between frames, which is generally a valid assumption.

**GPS Location Estimation:** Given the location of a feature in a video frame and the location of the camera when that frame was captured, basic geometry can be used to estimate the GPS location of that feature. By tracking a feature across multiple frames, we can get several such estimates. These estimates will not coincide because of errors in camera location, feature tracking, etc. However, given a set of video frames with corresponding camera and feature locations, a least squares technique can be employed to minimize noise in the estimated GPS target location. To enable accurate geolocation of targets, the students were taught to minimize the following equation:

$$\min_{\lambda_i, p} \sum_{i=1}^{n} [p - (c_i + \lambda_i x_i)]^2$$  \hspace{1cm} (1)
where \( c + \lambda x \) defines an estimate of geolocation of the target from a single frame, \( p \) is the overall estimation of location of the target in 3-D space and we have \( n \) frames. The results of this procedure are shown in the competition section below.

### 3.3 Air-frame and Autopilot Group

This group was responsible for airframe construction, and was also charged with the difficult task of system integration. This group’s function involved less novel design than that of other groups, but was perhaps the most critical. Their tasks included:

- Interfacing the algorithms designed by the other groups with system hardware
- Interfacing individual hardware components (GPS sensors, autopilot, camera, bomb dropper, etc.) into a single system
- Design and maintenance of low-level control algorithms for the aircraft
- Repair of broken/malfunctioning hardware

### 3.4 Results of semester’s work

To evaluate the progress of the teams throughout the semester, we held regular competitions between the teams. To demonstrate the final capabilities of each team, we show the rules and results of the final competition.

**Final Competition Rules:**

1. Each team will have a maximum of 25 minutes of flight time and 15 minutes of post-processing to complete the objectives.
   - (a) Multiple flights are allowed during this time, but each objective may only be scored once (i.e., you can take an additional flight to gain more points, but not to receive double points on things you have already done).
   - (b) Post-processing time is for viewing the video, identifying targets, and determining their locations.
   - (c) Post-processing will also include time for the teaching assistants to check your telemetry file and verify that you have not left the search area or entered no-fly zones.

2. Each team will be given a list of GPS waypoints that defines the boundary of the competition.
   - (a) Each boundary will run either N-S or E-W, but the border will not necessarily be convex.
   - (b) Halfway through the competition, we will give you a new file containing the boundary of an additional search area.
   - (c) This additional area will be rectangular, and will intersect the original search area.
   - (d) From that point on, you may search both areas for targets.

3. Each team will be given a list of GPS waypoints that define no-fly zones (these will also have N-S and E-W boundaries).
   - (a) The revised region may contain additional no-fly zones, but you must still avoid the original ones.

4. Five targets will be located in the search space.
(a) The targets will be $4 \times 4$ feet squares and consist of color markings.
(b) One of the targets will be a white Y with a blue background.
(c) One of the targets will be a white U with a red background.
(d) We expect target recognition to be accomplished by a human operator.

5. GPS localization.
(a) One of the main tasks is to accurately identify the GPS location of each target.

6. Autonomous bombing.
(a) Points will be given for dropping “bombs” on the U-flag.
(b) Bombs should be constructed from fishing sinkers and colored tails.
(c) Each team can drop at most five bombs (separately or all at once).

**Final Competition Results:** The final competition results are shown in table 1. In the table, the score breakdown for each team is shown. The target localization, and bomb dropping accuracy is indicated, and the total score is shown at the bottom. Two of the four teams (teams 1 and 3) were able to successfully complete the entire project (aside from some geolocation problems specific to the day of the final competition), and demonstrated their work by the final competition. Team 4 had hardware problems the day of the competition leading to worse results than they might have achieved some other day. Team 2 was unable to successfully recover from some hardware problems they experienced earlier in the semester.

4 CONCLUSION

Recently Brigham Young University introduced a novel course for undergraduates allowing them to understand and contribute to the field of mUAV systems. The course had a strong emphasis on mUAV concepts, and provided the students with important experience in putting together a complete working system to meet specified requirements. Novel concepts for these undergraduate students include algorithms for planning paths and searching an area, tracking features in images and geolocating targets from video, as well as designing, building, and planning to accomplish objectives as a team. The majority of teams were successful in meeting many of the objectives and produced working final products. We feel that this course will continue to make a positive and important contribution to the education of future students.

5 ACKNOWLEDGMENTS

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<table>
<thead>
<tr>
<th>Objectives</th>
<th>1 - Phoenix</th>
<th>2 - Plane ’Ol Team</th>
<th>3 - Strongbad Aviation</th>
<th>4 - X-49D</th>
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</thead>
<tbody>
<tr>
<td>Successful Takeoff (5)</td>
<td>5</td>
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<td>5</td>
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<tr>
<td>Auto-takeoff (10)</td>
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<tr>
<td>Auto-land (10)</td>
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<td>Accurate landing near a target (10)</td>
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<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Seeing target in video (5 for each target, x2 if completely done during autonomous flight)</td>
<td>10 (found 2 targets) x 2 = 20</td>
<td>0</td>
<td>10 (found 2 targets) x 2 = 20</td>
<td>15 (found 3 targets)</td>
</tr>
<tr>
<td>Localization of each target (10 for each target, x2 if completely done during autonomous flight)</td>
<td>0 (distances were greater than 50 meters)</td>
<td>0</td>
<td>14 (2 of 2 targets localized, accuracy 17m, 18m) x 2 = 28</td>
<td>10 (2 of 3 targets localized, accuracy 11m, 42m)</td>
</tr>
<tr>
<td>Accuracy of each bomb (10 for each bomb, x2 if completely done during autonomous flight)</td>
<td>0 (distances were greater than 50 meters)</td>
<td>0</td>
<td>18 (accuracy 17m, 26m, 32m, 41m) x 2 = 36</td>
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<tr>
<td>Entering no-fly zones (-10)</td>
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<tr>
<td>Leaving the boundary (-10)</td>
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<td>Any autonomous flight (5)</td>
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Table 1: Results of Final Competition
REFERENCES


