SCU Aerial Robotics Team- Experimentation with an Autonomous UAV Observation Platform

Ryan Becker, Chris Borowski, Ognjen Petrovic, Christopher Kitts, Neil Quinn Jr.
Robotic Systems Laboratory, Santa Clara University
Santa Clara CA 95053
Phone: 408-554-4382
E-mail: ckitts@me.scu.edu; Web: http://rsl.engr.scu.edu

Abstract- The use of an autopilot system in radio-controlled aircraft provides new and interesting possibilities. Autonomous aerial reconnaissance is one of the resulting useful applications. By utilizing Micropilot's MP2028g autopilot system and a customized .60 sized model airplane, an affordable yet effective UAV reconnaissance system was implemented. Through the use of event driven controls, a wireless video camera tracks a designated target as the UAV approaches and passes the ground object. By creating a tilting camera system, the total time a target is viewed by the camera increases, thus enhancing the accuracy of analysis by operators. To maintain the highest standards of safety, an additional RC receiver, servo, and battery pack facilitate the use of a secondary kill switch. This provides the ability to turn off the engine in the event of autopilot failure, primary RC receiver failure, or power systems failures thus limiting the magnitude of collateral damage. Safety and simplicity of design contributes to a competent and competitive autonomous UAV reconnaissance system. In addition, the project explores a multi-UAV approach utilizing several model aircraft flying in a follow-the-leader formation. The heart of this system, an easy to use GUI application, coordinates the flight of the two aircraft and manages the formation algorithm. Furthermore, the aerial robotics team explored the feasibility of multi-UAV formations for enhanced reconnaissance applications. Results of this work include the successful demonstration of automated follow-the-leader formation control.

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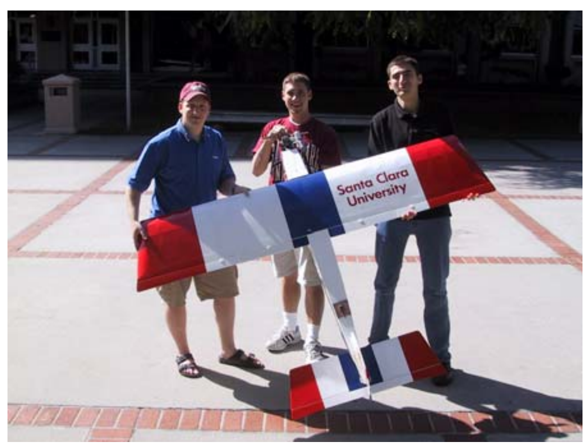

Figure 1- SCU's Aerial Robotics Team.

1. Introduction

The Santa Clara University (SCU) Robotic Systems Laboratory (RSL) conducts an aggressive, integrative research and education program in intelligent robotic systems. The centerpiece of this program is a set of yearly undergraduate design projects in which teams of senior students completely design, fabricate, test, and operate high quality robotic systems [1].

This particular project explores two uses for an off-the-shelf autopilot system from Micropilot. The first use is to enable an autonomous UAV reconnaissance system that can monitor designated targets and provide real-time video imaging to ground operators. The second use is to support the operation of a two-UAV fleet using an automated follow-the-leader formation flying strategy in order to ultimately provide enhanced reconnaissance capabilities. In support of these two objectives, the aerial robotics team developed a fleet of three aircraft for SCU to use as a basis for its experimental work in aerial robotics. Beyond the work reported here, this fleet will be used by future undergraduates, graduate students and professional researchers to perform compelling scientific investigations and technical demonstrations.

Figure 2- Aircraft taxiing to the pit area after a successful flight.

There are many applications and benefits to UAVs. The use of UAVs can accomplish many of the same objectives as manned missions, at a lower cost and risk. Some of the many applications include terrain mapping, search and rescue, environmental monitoring and collaboration of aircraft. Government agencies currently utilize the abilities of UAVs. Such aircraft include Predator, Global Hawk, Outrider and Shadow. [2] The project objectives associated with this project involve implementing a UAV observation platform and are consistent with these concepts.

Given the aforementioned advantages of UAVs it is natural to consider the potential benefits of using multiple robotic systems for the same applications. In general, multi-robot systems offer potential benefits such as increased coverage and availability, graceful constitution and degradation, and flexible reconfiguration for mission-specific purposes. The use of multiple UAVs for a single mission, however, also poses significant engineering challenges such as vehicle coordination, communication and integration. The second objective of this project was to explore some of these issues with a simple two UAV prototype system that implemented a follow-the-leader flight strategy.

The development and use of this robotic system and opportunity to work on multi-year robotics projects has served as the keystone for an integrated education within the SCU program. Overall, the mixing of students, engineers and scientists across a variety of educational levels and from a multitude of organizations creates a particularly stimulating environment for technical education, engineering innovation, and scientific discovery. [3]

This paper discusses the objectives of this project and describes some of the engineering decisions that went into the design features of this system. Safety aspects of the aircraft are also explored in detail. Some of the strategies that will be used for the competition are explained including the approach taken to most accurately determine the composition of the targets. The last section of the paper discusses the formation flight aspect and the methods used to enable the two aircraft to fly in formation.

2. Project Objectives

As previously stated, our two general areas of interest were to implement first, a single

UAV observation system, and secondly a simple two-UAV follow-the-leader system.

In order to achieve the first goal, our specific technical objectives required us to integrate the Micropilot autopilot into our flight system in order to achieve automated take-off, landing and navigation. For the AUVSI competition, the plane is designed to pilot itself through a series of waypoints. During the course of the flight, it will perform aerial observation. At the designated first waypoint, the aircraft will survey a 10 x 10 cement target with painted lines of various orientations and sizes. Aerial video will be broadcasted back to the operators for analysis. The orientation, size and number of lines will then be determined. After flying over the first target several times to ensure an accurate reading, the aircraft flies toward the second target. At the second target, the airplane will observe several vehicles and buildings. Analysis of video at this target will consist of a count on the number of objects, position in relation to the designated GPS coordinate and directional orientation of each object. After completing these tasks, the aircraft will then proceed home for landing.

To accomplish our second project objective, we had to do several things. First, a follow-the-leader formation flying algorithm needed to be designed. Secondly, it was necessary to create a ground control station that could coordinate the two aircraft, calculate ground trajectory information and handle communication between the two planes.

3. Technical Design

Many engineering decisions went into the design of this project. The architecture of all aspects had to be taken into account for successful integration of components. It was important to consider all the systems as many are interdependent on one another.

A. Airframe Selection

Forming the foundation for the entire project, it was essential have a stable airframe. In order to save on building time, it was decided that an almost-ready-to-fly (ARF) aircraft would be chosen. This approach was taken because the aerial robotics team is composed of three computer engineers, none of which have an aerospace background or experience designing airframes. An ARF was also important for compatibility reasons. If spare parts were required, it would be easy to obtain them from the local hobby shop. During the aircraft selection process several different airframes were tested. The investigation explored a high wing "Piper Cub" tail dragger, a low wing, fast and scale "Lancair" and a .60 size trainer. It was determined that the first two selections were poor choices.

Figure 3- Piper Cub

Our first experimentation was with the Piper Cub. The field in which many of the flight operations are conducted is rather windy making it difficult to taxi the aircraft and maintain a straight takeoff roll down the runway. Additionally, the characteristics of the tail dragger type of landing gear on the Piper Cub made it non-conducive for this experiment. When the plane was equipped with sensors, the added weight resulted in a longer time for the tail to rise off the ground. The wing spars also posed another challenge as their attachment mechanism prevented easy access to the fuselage. This attributed to making internal modifications difficult. Furthermore, the Cub proved to handle poorly in high wind conditions because the wings would easily get caught in a gust and the plane was susceptible to blowing over. In one instance, similar to a kite, the aircraft was actually blown backwards when it was idling on the runway.

Figure 4- Lancair

To try and help solve some of the issues that plagued the Cub, the next aircraft tested was a sleeker, low wing scale aircraft; a Lancair. However, the Lancair provided a similar plethora of challenges that the Cub did. The building time on the aircraft, due to its scale attributes was approximately 50 hours, not the anticipated 10 hours an ARF usually requires. The wing profile and surface area on this particular aircraft are also small resulting in a high stall speed. These factors contributed to a high takeoff, approach and landing speed. The accurate scale and realism of this aircraft also limited the carrying capacity making it less suitable for a UAV equipped with an array of sensors. For example, it is much more stable to hang the weight from the plane than to set the weight on top of the wing. An aircraft is more stable in a high wing configuration than the low wing design. Furthermore, both the Piper Cub and Lancair were more expensive than the .60 sized trainers that were finally selected for the project. While the Lancair and Piper Cub were inappropriate for the UAV project, they assisted the team in several ways. Through the challenges and obstacles that the two aircraft provided, the team was able to identify the traits of good UAV airframe.

Figure 5- Super Sportster .60

The .60 size trainer was chosen because it provided an adequate payload and internal volume to carry the required sensor equipment. In addition, the aircraft wasn't physically too large to work with, transport and store. The chosen aircraft, a Super Sportster .60 is available as an ARF (Almost Ready to Fly) and was quick in assembly time. The tricycle landing gear configuration allows for easy ground handling, even with a modest amount of wind. The symmetrical airfoil helps the plane track straight through the air and the large wing area permits it to fly stably through the entire speed envelope. Operational flaps contribute to smooth handling and a higher payload at slower speeds. Overall, the stability and dependability of the Super Sportster .60 allows the focus to be on more important tasks such as learning and utilizing the full potential of the autopilot system.

B. Engine Choice

With an airframe selected, the next engineering decision was to choose an engine to power the aircraft. As SCU's Aerial Robotics Team had previous experience with OS Engines, a .61 FX was selected to fulfill this need. While it has proven to be quite a workhorse, it has left a few things to be desired. As a two-stroke glowfuel engine, the exhaust is very oily and a considerable amount of time is put into cleaning the planes and equipment after every day of flying. The weight of the equipment inside the plane in addition to the drag of the belly mounted camera is enough to require nearly full throttle during a fully loaded flight. While this engine gets the job done, a larger, more powerful 4-stroke engine is desirable. An engine of this type would create an almost non-existent exhaust residue and have enough reserve power to quickly climb to higher altitudes.

For the AUVSI competition, the team decided to continue working with the original .61 FX to limit the fuel consumption rate. As fuel economy is one of the judging categories, it's important to limit the consumption rate and consequently, a smaller engine is more economical.

C. Power Systems

With a suitable aircraft and engine selected, the power distribution system for the plane servos and payload needed consideration. The aircraft utilizes four separate power systems for redundancy and safety purposes. Upon consideration of a single high energy Lithium Ion battery, it was declined for several reasons. First, since different components have special voltage requirements, simplicity dictated avoiding the hassle of integrating custom designed regulators to power all the on board equipment. Secondly, while payload weight was a concern, evaluation of the aircraft's capacity indicated that using a redundant four-battery system was an acceptable tradeoff. In other words, the benefits of additional batteries outweighed the more efficient single battery power system. Table 1 shows the break up of power systems on board the aircraft.

Purpose	**Battery Size**
Autopilot System	4.8V 1800 mAh NiCd
Flight Servos	4.8V 2700 mAh NiMH
Radio Modem, Video Reconnaissance Package	12V 1100 mAh NiMH
Redundant Engine Kill Switch	4.8V 600 mAh NiCd

Table 1- Breakup of the Power Systems on board the aircraft.

The autopilot and flight servos were placed on a separate battery in the event of a high current draw by one of the servos. This helps to ensure that the autopilot voltage will not drop too low, resetting the flight computer mid-flight. A high capacity servo battery was also selected to support the 7 operational servos and to reduce the risk of running out of power. The selection of a 12 volt battery for the video package and modem was simple due to their voltage requirements. This power system is considered a secondary system as the aircraft could still function normally should this battery fail. The aircraft also has a separate battery, receiver, antenna and servo to control a redundant engine kill switch. The use of this emergency switch provides the ability to limit the range of the aircraft by stopping the engine in the event of an autopilot or main servo battery failure.

Figure 6- Inside the UAV

D. Communication Links

For physical control of the plane, the aircraft supports two primary means of communication. These include a wireless radio modem made by Maxstream and the traditional RC link.

Two modems were considered for serial communication with the aircraft. The first, a modem by Richochet, cost only ten dollars making them very attractive initially. Upon testing however, there were several concerns. The modems, while able to maintain a connection over a long distance, were very difficult to connect initially. It was necessary to dial up a particular modem followed by a 30 second wait time while 'hand-shaking' occurred. Even when connected, the modems had many dropouts making data transfer unreliable. The modems were also much heavier and took up too much valuable cargo space.

The second choice purchased from Maxstream greatly simplified the wireless connection process to the autopilot. The initialization process simply involved turning on each modem. Even more encouraging was the lack of dropouts and range capability. After testing over a 2 mile range, the Maxstreams were determined more than acceptable and they were integrated into the system.

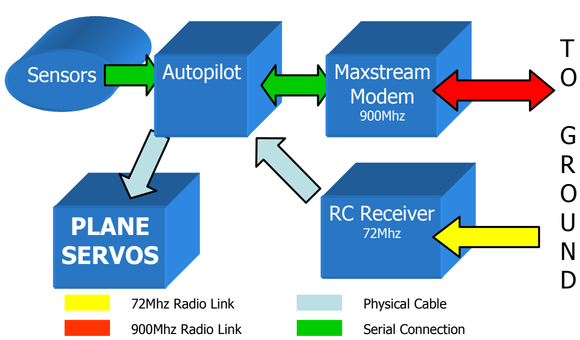

Figure 7- Aircraft Data Flow Chart

The RC link was selected because it provides a standard interface for the plane. It is also well tested, approved by the FCC and safe when operating around other aircraft. The aircraft are also not operated outside line of sight so it was not necessary to explore other, longer range means of aircraft control. The RC link allows for the pilot to fly the aircraft manually. This is considered pilot in control mode (pic). Through a switch on the transmitter, the pilot has the ability to switch between computer in control (cic) mode and pilot in control. The radio modem provides a real-time link to the plane and a way to interface with the autopilot system in-flight and permits the upload of flight-paths and commands. Real-time information is also received from the aircraft such as airspeed, altitude, and positional location through the radio modems.

E. Video Reconnaissance Package

The video reconnaissance system consists of a package that mounts to the bottom of the aircraft. Rubber bands are used to attach the camera box as in the event of a crash, the box can break away from the plane thus limiting damage to the equipment housed within.

Figure 8- Screen shot of real-time aerial imagery from plane.

The camera and transmitter system, made by wirelessvideocameras.com, were selected due to their ability to transmit long range (currently 10 miles with a directional antenna). It took experimentation with several other less expensive camera solutions to finally settle on this particular product. Other systems were disappointing due to their limited range capabilities. The maximum range of the other systems peaked out around 150 yards before the signal became fuzzy. For this project it was important to have a solution that could work effectively at least one mile away because of our flight range.

The system selected consists of a CCD camera, transmitter and servo to control tilt. This provides the ability to look anywhere between the forward position and twenty degrees aft. The camera system was designed with this ability to solve several problems. First, it eliminates the need to carry several stationary cameras looking in different directions, thus reducing the weight. Additionally, a video camera is more effective than a still camera because operators can receive a continuous stream of images in which to analyze. It also eliminates the need to 'time' the moment in which to take a photo when passing over a target. Using the autopilot, the ability was added to track a target as the aircraft flies over it, providing the most amount of viewing time possible. This is accomplished by using events to drive the position of the camera. An illustration of this appears in appendix B.

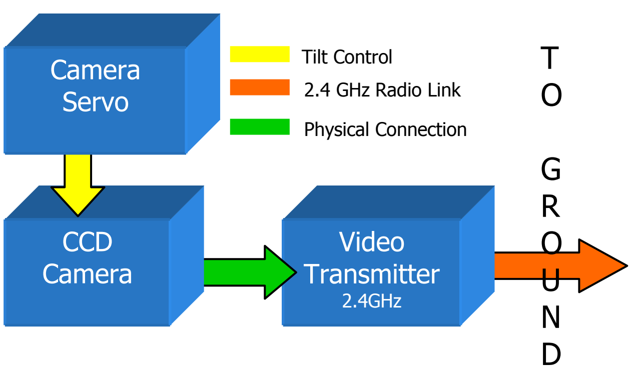

Figure 9- Video Data Flow Chart

The camera tracking process is as follows. When creating a flight plan for the aircraft and there is a designated location to observe in mind, a series of waypoints are created at specified distances leading up to a target. As the plane crosses the path leading up to the target, it gradually shifts the camera to a downward position so that when the aircraft crosses the target, the camera is looking straight down. With the ability to stream the video live to the ground, an operator has an advantage in that they can analyze the data in real time as opposed to reviewing still photos after the flight. Figure 5 details the data flow for the camera system.

4. Safety

As one of the goals of this project was to establish a new aerial fleet at Santa Clara's Robotics Systems Laboratory, the institution of safety procedures was very important to implement from the start. Several fail-safe features have been implemented through measures built directly into the plane as well as detailed checklists that are followed prior to flight. A brain storming session enabled the generation of some of the safety features that could help prevent some of the worst case scenarios that could happen with the aircraft. Battery failures, loss of one or both RC receivers, autopilot malfunction, and structural failure were considered. By taking these ideas to mind, the systems were isolated so that in the event of one failure, it would be possible to minimize damage to the aircraft and equipment and even possibly recover from the fault.

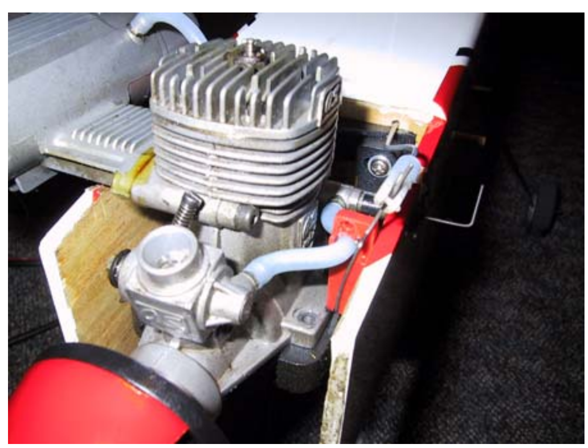

Figure 10- An engine cutoff switch is mounted to kill the engine in the event of a systems failure.

Additionally, in order to fly at one of our testing facilities, Moffett Field, located at NASA Ames Research Center, it was necessary to present the project to a NASA Flight Readiness Review board. Through demonstration of safety checklists, the redundant engine kill switches and their experience, the aerial robotics team demonstrated the ability to fly safely in Class D Airspace and was certified by the board to fly on their military airfield. With the larger flight line provided by Moffet field, it gave the team the chance to "stretch their legs" testing the effectiveness of the video system and their skill at aerial observation.

5. Competition Strategies

The effectiveness and efficiency in a flight plan plays a large role in determining who wins the AUVSI competition. This path directly reflects the time needed in the air, fuel consumed and accuracy of aerial images. Since this is such an important part of the competition, there are several strategies we follow during the flight plan creation process.

In any flight plan that's created, a combination of manipulating the waypoints in the GCS Graphical User Interface and manually editing the .fly files is utilized. This allows for the visual placement of desired waypoints and then provides the opportunity to fine tune the path of the aircraft by editing and adding specific commands. When the purpose of the flight is aerial reconnaissance, the targets must be approached in a particular way. A series of waypoints before and after the target are laid out in a straight line. The design of the camera mount requires this as the plane must be flying straight and level to accurately capture the designated target. If the plane is banked, it would visually miss the target. See appendix A for an illustration of a typical flight plan designed for aerial observation.

To date, practice sessions have been very successful in the observation of objects aerially. The SCU team has confidence in their ability to take the plane off, fly a series of designated way points and land under manual control. Currently, autonomous takeoffs and landings are being practiced and that ability may be utilized for the competition.

6. Formation Flying

One of this project's goals was to explore other possible uses of the autopilot system. Therefore, a project was also undertaken to develop multiple, autonomous aerial robots that fly in formation to achieve coordinated visual reconnaissance. This proves to be a challenging engineering feat; however the contributions to the aerospace industry outweigh the risks and difficulties involved in this design process.

As depicted in Figure 11, the formation flight system consists of a human-piloted lead plane and an autonomously flown chase plane that follows the lead plane's flight path. As the lead plane is flown, its trajectory is determined through an on-board GPS receiver, and this data is transmitted to the ground control station. Software at the ground control station filters this trajectory in order to generate suitable waypoints for the chase plane. These waypoints are used to continuously update the chase plane's flight plan which is then uploaded to the Micropilot unit on the chase plane. The flowchart in Appendix D depicts this process.

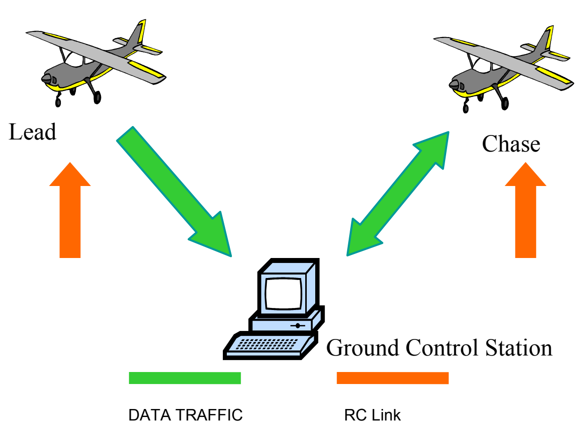

Figure 11- Design overview of data flow among aircraft

Execution of this ground control station processing is implemented by a real-time event driven software application developed by the project team. The program's graphical user interface, shown in Figure 12, displays GPS location, airspeed, and altitude telemetry for both planes; the interface can also plot the paths of the planes in real-time in both two and three dimensions.

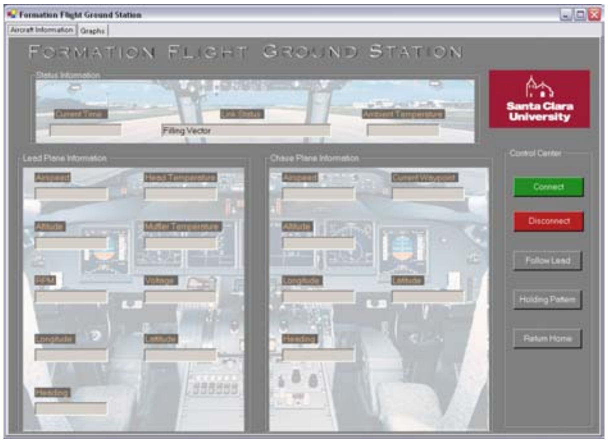

Figure 12- Image of our ground control station software.

In limited testing to date, this system has been used to successfully demonstrate follow-the-leader behavior. As shown in the plot in Figure 14, the chase plane faithfully followed the human-piloted lead plane through a simple maneuver with an average accuracy of approximately +/- 50 meters over the duration of the maneuver; this accuracy is consistent with the rated accuracy of the GPS receivers used for this demonstration. In early June, more extensive testing and evaluation of this capability will be performed at Moffett Field.

Figure 13- Aircraft in 'Follow the Leader' Formation.

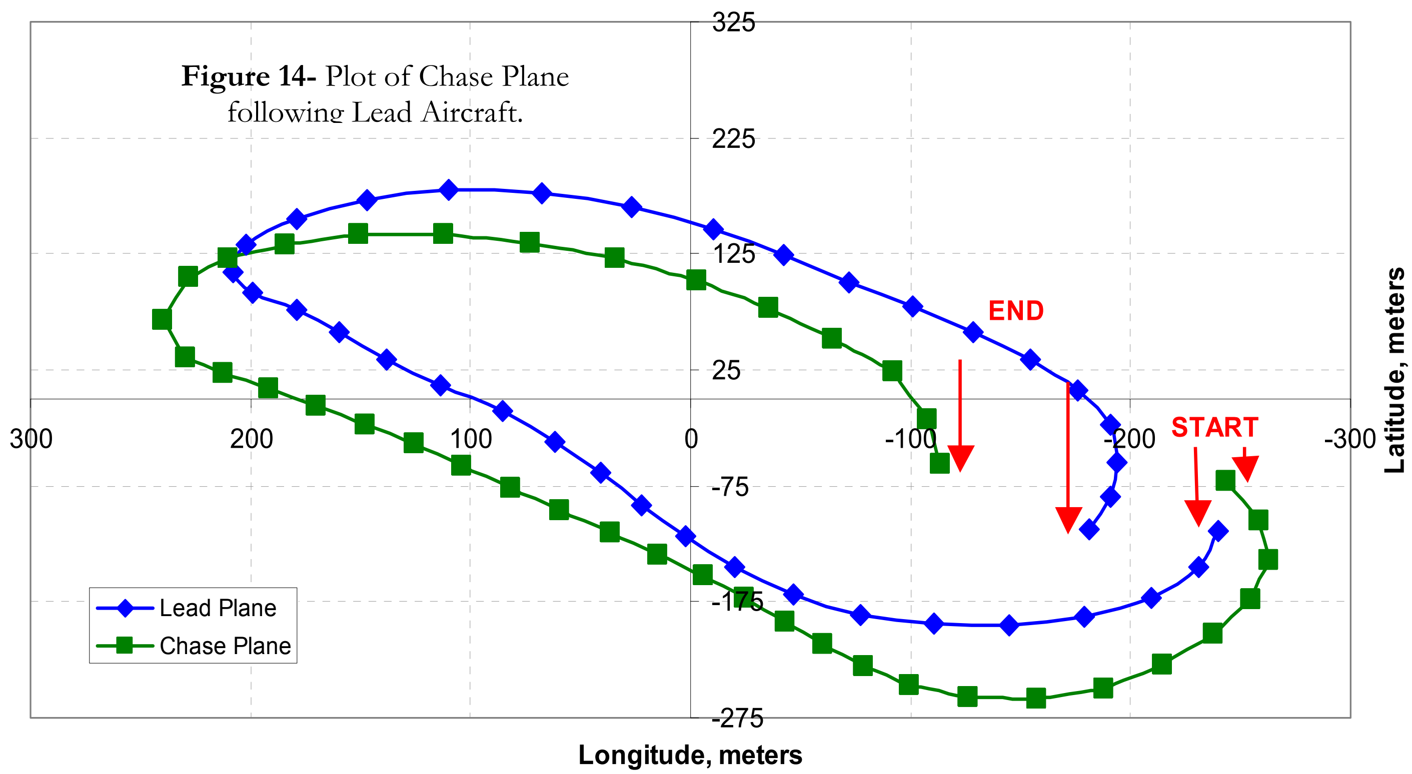

Figure 14- Plot of Chase Plane following Lead Aircraft.

Overall, these results are quite positive for an initial implementation of UAV formation flying. As a result, the team has entered into discussions with several external collaborators in order to determine specific requirements for using multi-UAV formations in real applications. Specific applications under consideration include estuary analysis with photos from multiple UAVs being incorporated into a regional mosaic, fire monitoring with UAVs tracking assets and monitoring hotspots in a coordinated manner, and object visualization using two UAVs in a real-time formation to provide stereo imaging capability.

7. Conclusions

This project has successfully demonstrated several things including an autonomous 'follow the leader' formation flight algorithm and an inexpensive UAV reconnaissance system. The team has established a fleet of aerial vehicles for Santa Clara University to become a research platform for future projects. Many of the design choices in this project were determined by cost, compatibility with other components and ease of integration. Safety was an extremely important factor for this project as a precedent was established for precautions, rules and guidelines in working with SCU's aerial fleet. This team will succeed in AUVSI's student UAV competition by effectively utilizing an aerial observation system that provides more accurate real-time information to operators. In addition, the autopilot system provided by Micropilot coupled with our techniques will guide the aircraft to a successful finish.

Acknowledgements

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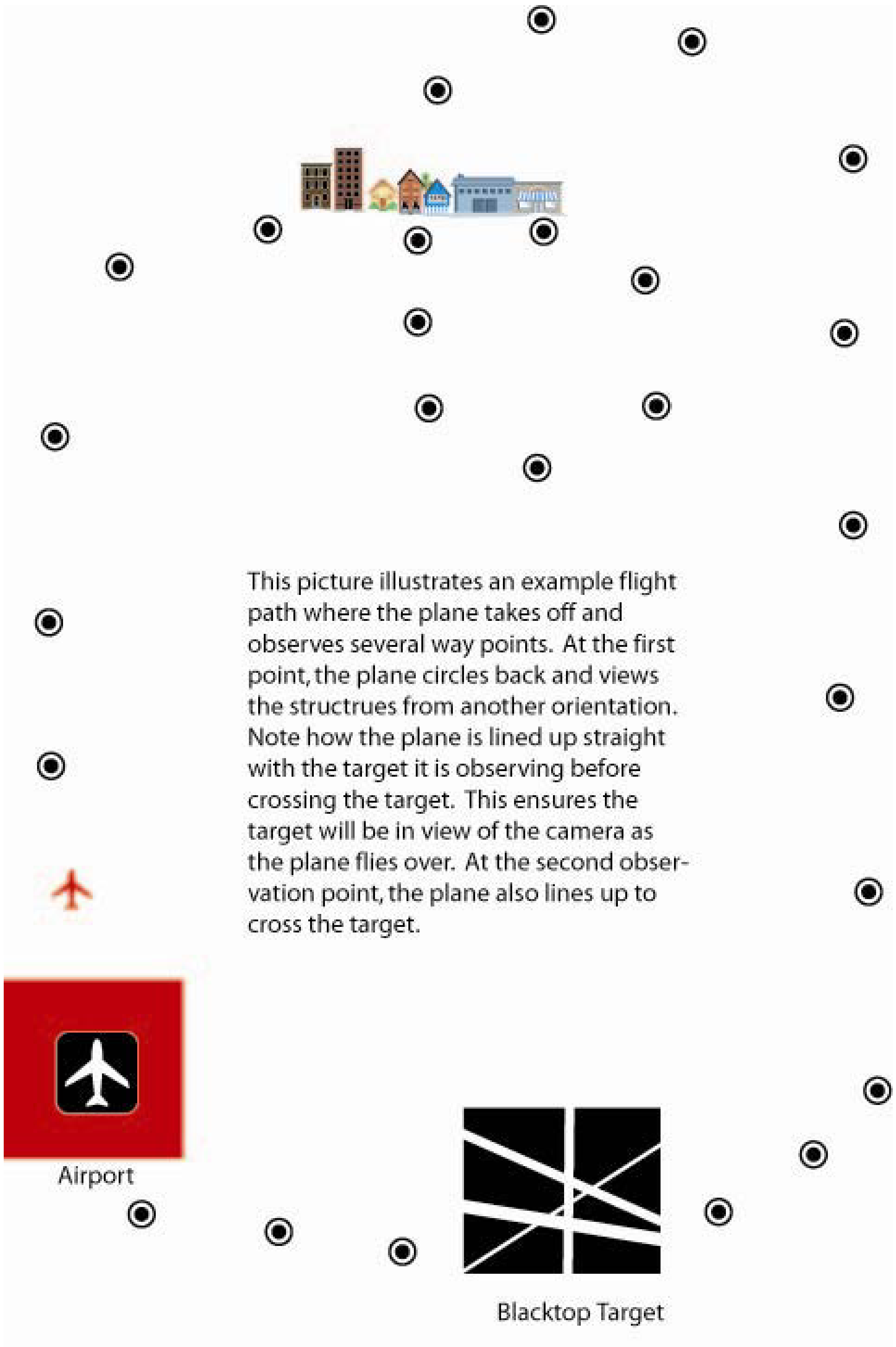
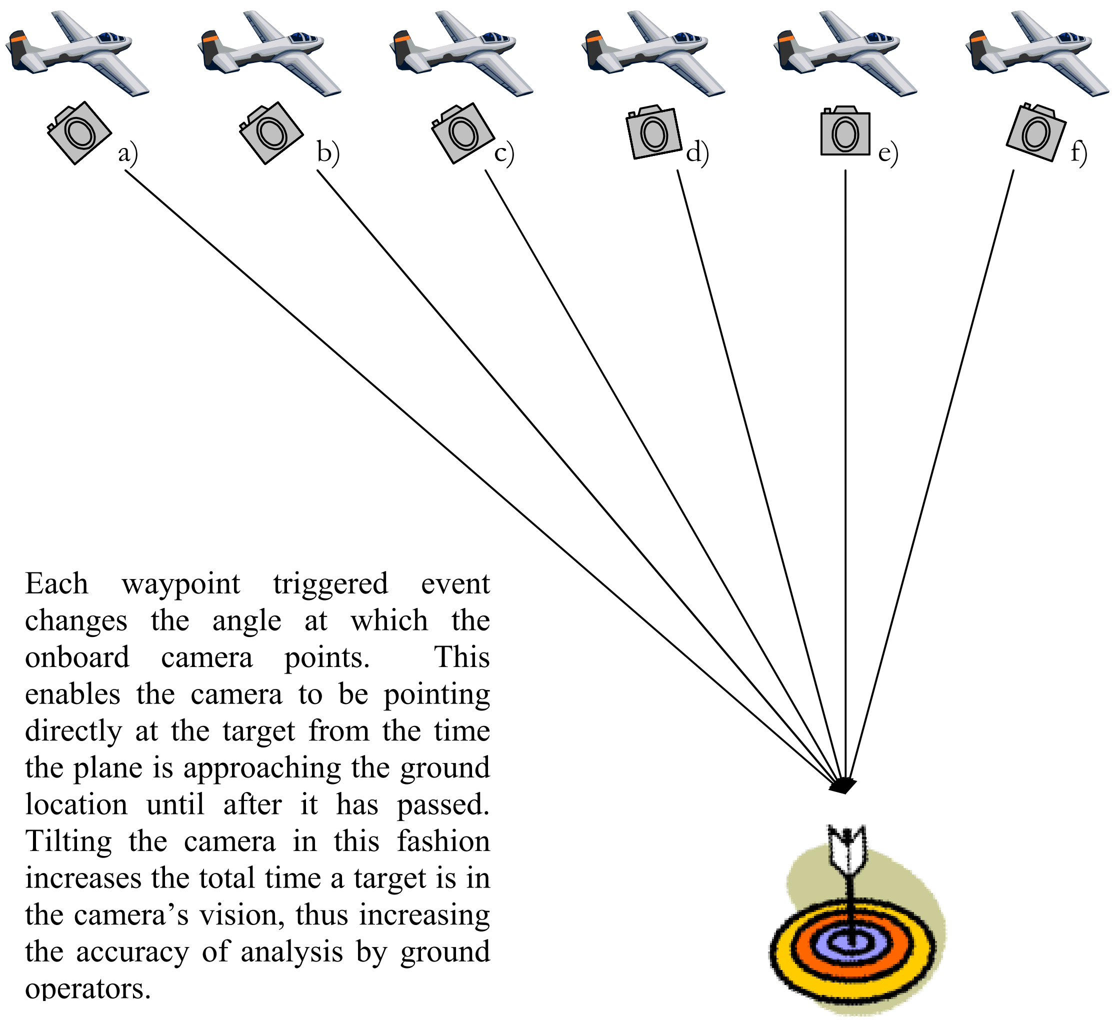
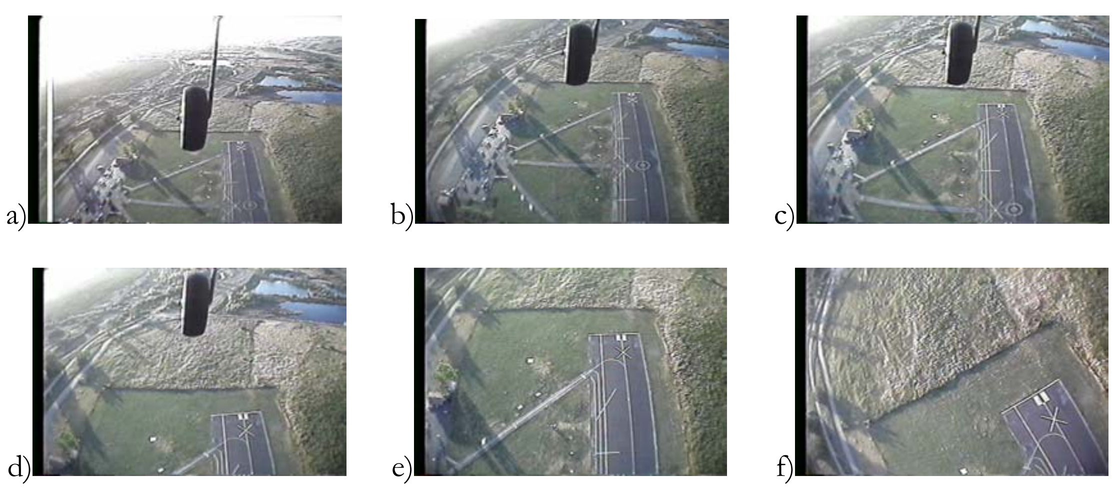
Appendix A- Illustration of aircraft flight path



Appendix B: Demonstration of an event driven aerial reconnaissance technique



Each waypoint triggered event changes the angle at which the onboard camera points. This enables the camera to be pointing directly at the target from the time the plane is approaching the ground location until after it has passed. Tilting the camera in this fashion increases the total time a target is in the camera's vision, thus increasing the accuracy of analysis by ground operators.



Appendix C- Ground Control Station Flow Chart:
Cycle repeats once every second.