

# Brigham Young University MAV Team

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## Abstract

For the U.S.-European Competition and Workshop on Micro Air Vehicles, Brigham Young University is using a Procerus Technology autopilot system with an in-house developed user interface designed specifically for this competition. This system includes an embedded autopilot, wireless communication hardware, and ground station hardware and software. The ground station is used for mission control and video processing. It enables a MAV operator to fly completely autonomously, navigating waypoints based on operator input. Using a video signal transmitted from the vehicle, ground station software gives human operators the ability to effectively identify, geo-locate, and track ground targets through video stabilization and point-and-click control. The BYU system is very safe due to fully electrical hardware and implemented failsafes.

# 1 Introduction

As technology has advanced, aircraft and avionics packages have continually decreased in size to the point where fully autonomous vehicles are now able to be crafted in very small systems. Brigham Young University has developed a small, lightweight autopilot for Micro Air Vehicles (MAV), which has led to considerable development of the small, electric, fixed wing platform. Our students have created a new generation aircraft with a wingspan of just 40 centimeters for entry in the U.S.-European Competition and Workshop on Micro Air Vehicles.

The vehicle system uses a compact yet robust airframe which is designed to be fully autonomous flight. The vehicle transmits video and wireless radio through separate channels and is laid out to minimize interference between the signals.

The autopilot, one of the smallest in the world, has integrated solid-state gyros and accelerometers to provide estimates of all attitude angles and rates which allows for reliable navigation. Operators at the ground station use vector-field path planning to defined paths for waypoint navigation. The ground station relays important telemetry data to the operators and gives them all complete control over the autopilot configuration in order to successfully complete the mission. Video, telemetry, and navigational information are at their fingertips. To provide stability and safety, failsafes have been implemented for loss of communication, loss of GPS, low battery voltage, and loss of control. Response to each individual failsafe varies depending on what makes sense on the given situation.

The BYU Multi-Agent Intelligent Coordination and Control Laboratory (MAGICC Lab) MAV system is a collection of proven and newly developed technologies fused into a platform that is robust, safe, and capable of handling operator-defined objectives.

## 2 MAV System Overview

The MAV system consists of a custom-built airframe outfitted with an autopilot with navigation sensors, a GPS unit, computer vision hardware, and a ground communications link.

### 2.1 Airframe

The MAV airframe is a twin-boomed pusher aircraft (see Figure 1). The fuselage is designed to hold the electronic equipment in a compact, yet protective design.

The wings and fuselage are made from extruded polypropylene (EPP) foam, cut and shaped into the desired layout. The booms are made from carbon-fiber rods, which have a high stiffness-to-strength ratio. The empty weight of the airframe is 193 grams and the payload weighing 275 grams yields a total weight of 468 grams.

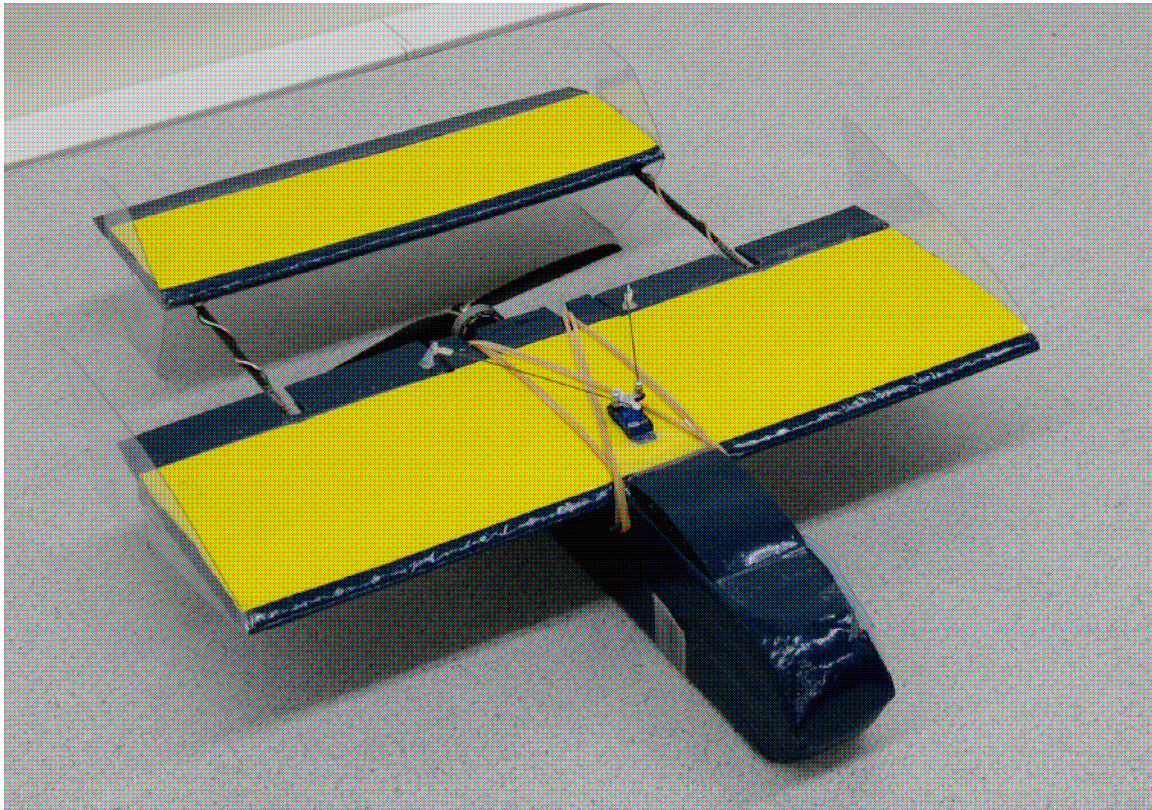


Figure 1: The Micro Air Vehicle pictured above has been designed, built, and outfitted at Brigham Young University for the MAV competition.

## 2.2 Computer Vision Hardware

The system uses a KX-141 Color CCD camera from Black Widow Audiovisual [1], and a similar yet much smaller CCD camera from Super Circuits. Both NTSC cameras, transmit 30 frames per second of 640x480, and 540x380 interlaced color video. Crisp, clear video is vital for the success of any mission requiring target imaging. Due to continual motion of the MAV, interlacing causes degradation of the video. The ground station software is capable of de-interlacing the video stream by taking one field of the interlaced video and interpolating to generate the second field.

To send and receive the video stream, we use a transmission system designed by Black Widow A/V (see Figure 2), which transmits on the 2.4 GHz

frequency using a 600 mW transmitter. The video is received on the ground and fed into a K-World frame grabber, which captures the video stream for processing in the ground station. A detailed description of the software video processing and display can be found in section 3.4.3.



Figure 2: The MAV video system consisting of video cameras, transmitter and receiver.

## 2.3 Data Link

Communication between the vehicle and the ground station is accomplished through a wireless 2.4 GHz link. Both the airplane and the ground station are equipped with wireless modems, which have a range of over 1 mile in line-of-sight conditions. The modem is the MaxStream Xbee-Pro (see Figure 3 below). This small yet powerful modem makes for a very lightweight solution for controlling a MAV. The modem unit weighs just 0.1 ounces.



Figure 3: MaxStream Xbee-Pro 2.4 GHz Modem

The MaxStream modems transmit at a baud rate of 115200, which allows for rapid transmission and reception at the MAV and ground station. Though



designed for multiple agents to communicate simultaneously, for this application the communications system will operate in streaming mode. This allows the MAV to transmit its telemetry at an adjustable rate (usually 5-10 hz). The ground station sends commands at a specified rate. Both receive and verify telemetry using a CRC checksum method, allowing for robust communication and rejection of erroneous signals.

## 2.4 RC Hardware

The RC control hardware used is a Futaba T9CAP. It interfaces with the system through a trainer cable plugged directly into the data link hardware. Commands from the radio are relayed directly to the plane so that the RC pilot control is independent from the computer's control.

## 2.5 Navigation System

To navigate autonomously, the MAV uses a GPS unit produced by Furuno[2]. Rate gyros on the autopilot are used to smooth the GPS data and allow for a

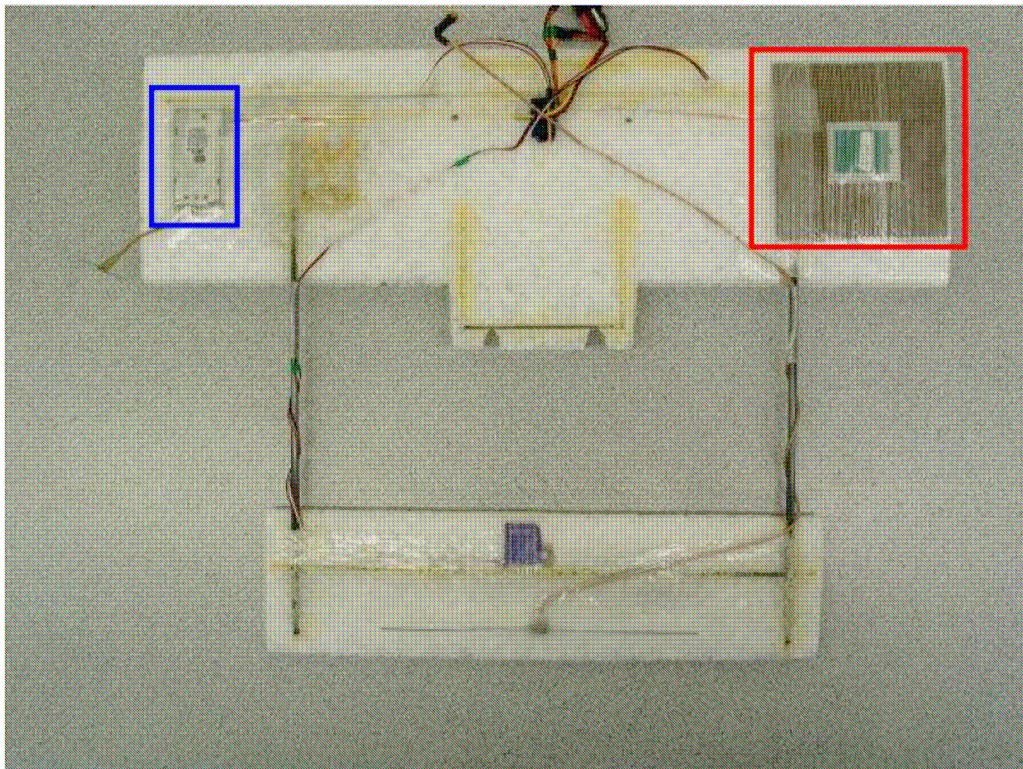


Figure 4: This view shows the airplane from below with the fuselage removed. In the left box, is the video transmitter. The Furuno GPS unit with ground plane is surrounded by a box on the right.

better estimate of heading for the control system. The Furuno GPS operates at 1 hertz providing a ground position, which is typically accurate to within 5 meters. A small copper ground plane acts as the ground for the GPS unit helping to minimize interference. Both are installed in the wing of the aircraft, attempting to minimize noise from the other sensors and affiliated wiring.

## 2.6 Payload

The payload system of the MAV is designed to drop a paintball accurately on a target. The autopilot calculates the ideal drop position from the current location, air speed, wind speed, altitude, and information from vision based navigation. When the plane achieves the calculated ideal drop position, the plane cuts throttle, a servo actuates a sliding drop door, and the paintball falls on the target. The aircraft then resumes normal flight and proceeds with its next mission objective.

## 2.7 Autopilot - Method of Autonomy

The aircraft carries a Kestrel™ Autopilot (Figure 5) manufactured by Procerus rtechnologies [3]. Weighing just 16.65 grams and measuring 2 x 1.37 x 0.47 inches (5.1 x 3.5 x 1.2 cm), the autopilot is small, light, and robust. The autopilot system uses a Rabbit Semiconductor RCM 3400 microprocessor which can be programmed using Dynamic C (a variant of ANSI C) using special operators to take advantage of the Rabbit microprocessor's intrinsic abilities.

A comprehensive description of the hardware and software architectures used and the control algorithms associated with the autopilot can be found at [4].

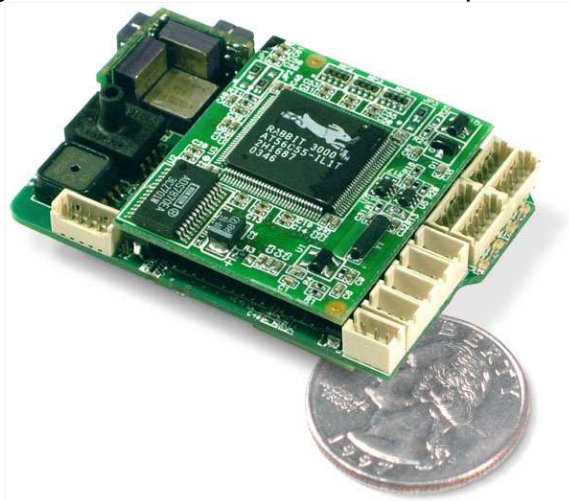


Figure 5: Kestrel autopilot with modem attached. (Photo courtesy of Procerus Technologies R, [www.procerusuav.com](http://www.procerusuav.com))

## 2.8 Sensors

The Kestrel™ Autopilot contains a central processing unit, avionics sensors, and input/output ports all in a very small footprint as shown in Figure 5. The Kestrel™ motherboard houses the Rabbit RCM 3400 microprocessor which monitors all of the sensors and communication with the ground station. Integrated into the autopilot is a barometric sensor, calibrated to the takeoff altitude, which monitors the MAV's height relative to home. A pitot tube connects to a differential pressure sensor on the autopilot to provide a dynamic pressure measurement for calculating airspeed.

In addition, the autopilot houses a six degree-of-freedom (6-DOF) inertial navigation unit with 3-axis solid-state rate gyros and accelerometers. The rate gyros double as temperature measuring sensors, and all accelerometers and gyros use temperature-compensation to account for nonlinearities in measurements. The GPS unit connects via one of four available serial ports. An additional analog input port is also available for sensor reading.

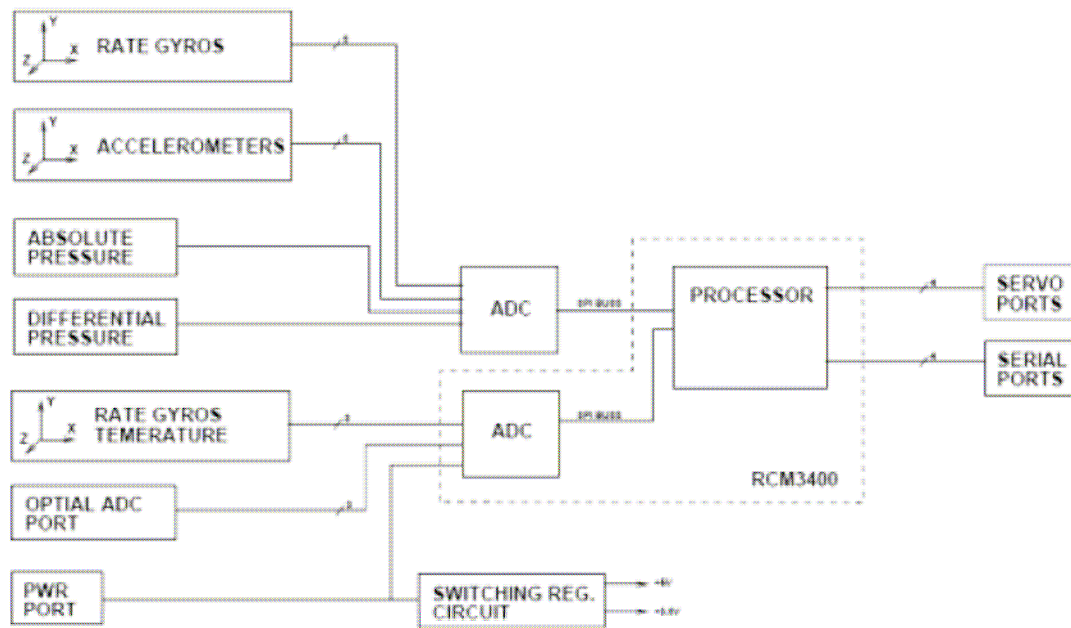


Figure 6: Kestrel Autopilot block diagram showing sensor and actuator connectivity with the microprocessor.

## 2.9 Actuators

Four servo ports run by 10-bit pulse-width modulators make up the actuator suite. Servos are attached to push-pull rods connected to control surfaces in the same manner as in standard RC controlled aircraft. Channel 1 runs the aileron



servo, channel 2 the elevator and channel 3 the throttle. Channel 4 is used to control the bomb bay door. All servos are powered from the speed controller, which governs the motor and provides 5-volt output to the other servos. A detailed view of the sensors and actuators and their connection to the autopilot processor is pictured in figure 6.

## 3 Software and Control

### 3.1 Control Methodology

The autopilot uses proportional, integral, derivative (PID) control with successive loop closure controllable from the ground station. The graphic in figure 7 shows the ground station PID Loop Selection interface that allows the operator to select sets of control loops. Typically, the MAV is flown under full autonomy, meaning that pitch, pitch rate, roll, roll rate, and altitude are all computer controlled. Waypoint patterns, where the operator designates specific waypoints in the ground station map window, is the default navigation mode.

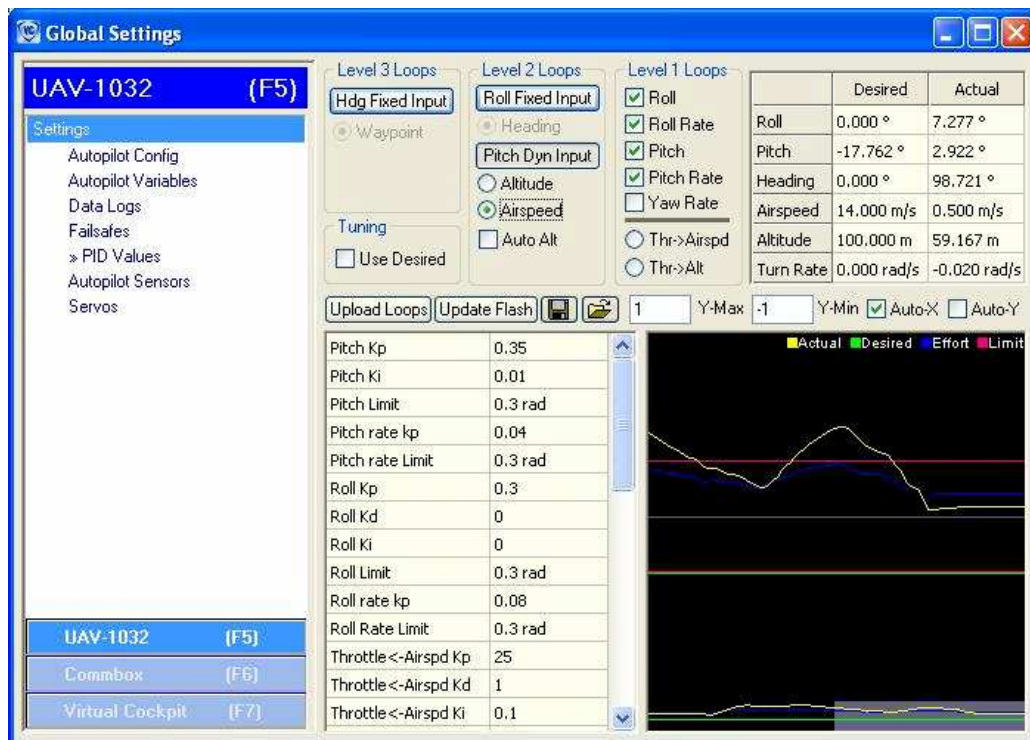


Figure 7: PID Selection tools within Virtual Cockpit. Individual loops and control schemes can be monitored and tuned.



PID control maintains very tight control of the aircraft. Graphs in the Virtual Cockpit help operators tune the control gains in order to reduce overshoot and oscillation. The lateral and longitudinal dynamics are separated for control design purposes, but both function together to provide complete stability. To more clearly illustrate how the controller works, the lateral autopilot will be described.

The lateral autopilot uses feedback from roll and roll rate measurements to correct errors in roll. When flying from one waypoint to another, a desired heading angle is generated which keeps the MAV flying along the line connecting the two waypoints. In order to maintain this desired heading, the plane is commanded a roll angle, which will take the shortest route to the desired heading while saturating the roll angle command within defined limits. Once the plane has approached the desired heading, the PID controller automatically reduces control effort in order to smoothly approach the waypoint path. The longitudinal autopilot coupled with the lateral autopilot and smart altitude control allow the airplane to follow complex trajectories to autonomously complete the entire mission.

Several navigation techniques are possible when flying waypoints, including sophisticated algorithms which allow for smoothing of trajectories. All navigation calculations take place on the autopilot, reducing the amount of information which must be transmitted from the ground station.

### 3.2 Command Structure

The autopilot controls the plane and is interfaced in two ways, pilot-in-control (PIC ) and computer-in-control (CIC). PIC means the pilot is controlling the plane and CIC means that the autopilot has control of stability and navigation. The command modes are toggled using a switch on the RC controller that connects to the communications box through a trainer cable. The communications box connects to the computer through a regular RS-232 serial port. The safety pilot always has the capability of taking control of the aircraft if anomalous behavior should occur or if manual landing is desired.

### 3.3 Autonomous Take-off and Landing

Our MAV employs algorithms for autonomous takeoff and landing. The aircraft requires a hand-thrown launch. After the MAV is launched, the autopilot utilizes the aircraft's pitch and throttle to increase speed. When a specified airspeed is reached, the MAV pitches up and begins to spiral around the takeoff location while gaining altitude. Once the MAV reaches its desired altitude, it exits takeoff mode and begins waypoint navigation. If there are no waypoints entered, the MAV continues to loiter above home until it receives updated commands.

For autonomous landing, the operator specifies a landing point and an

approach point. The MAV will spiral around the approach point at a specified airspeed and descent rate. After reaching a specified altitude, the MAV descends directly towards the landing location [5].

### 3.4 Ground Station

The ground station handles all communication with the MAV, including sending navigation commands and tuning PID controller gains. The MAGICC Lab has developed a robust software interface to fulfill these goals called Virtual Cockpit (VC) (Figure 8). Virtual Cockpit is a Windows-based ground station program designed for direct control of the Kestrel™ Autopilot. The ground station gives operators a useful mission-planning interface including a map display, video display, and a mission specific custom interface display.

#### 3.4.1 In-House Developed User Interface

In order to adapt quickly and efficiently to the various missions in the competition, we developed an interface which has different modes designed to best task the airframe. There are four different mission specific modes: Geo-location, Bombing, Identification, and Urban Canyon. In the Geo-location mode, relevant data and control are given to the vision software and user (such as attitude and plane location), to best locate and object on the ground. In Bombing mode, data specific to a free falling object are given to the autopilot along with a user set bias. In Identification mode image, enhancement software is used on the video feed (edge detection, color enhancement, de-interlacing). Lastly in Urban Canyon mode, navigation is done by updating a waypoint based off of a feature tracked object by a forward looking camera.

#### 3.4.2 Map Window

The Map Window provides operators with the ability to see where the aircraft is located relative to home position. It also shows current and past locations laid over a map of the area. From this window, the operator can input various types of waypoints to execute mission objectives. The waypoint list can be dynamically edited, providing real-time retasking capability.

#### 3.4.3 Video

The Video tab gives the operator the ability to view video coming down from the aircraft. The video window has the capability of loading several different vision algorithms contained in external files. The vision area displays video streamed from the MAV, and has the capability of switching between a forward looking and a downward facing camera.







Figure 8: Virtual Cockpit provides a visual update of the vehicle's position and heading through the map window. Waypoints are easily placed and rearranged for accurate waypoint navigation and mission control.

## 4 Safety Procedures

Safety is a vital part of any system, especially when failure of those systems can result in dangerous behavior to both operator and bystanders. Recognizing the need for safety precautions, the BYU MAGICC Lab MAV system has the ability to manually override the autopilot and has built in fail-safes in the case of system failures. A preflight checklist is also followed to ensure proper performance of the system before the MAV is put in the air.

Fail-safes are a system of preset instructions used to control the MAV in the event of a subsystem failure. Fail-safes ensure that the plane will either return home or descend in a controlled manner based upon the type of system failure.

### 4.1 Return to Base fail-safe mode

When the return to base failsafe is activated, the aircraft deviates from its course and proceeds towards a predefined GPS location, denoted as home, established during the preflight check. Upon arrival at home, the MAV will loiter above the home location for 5 minutes. If the malfunctioning subsystem begins to function properly, the MAV will reestablish its heading to complete mission objectives. If the system is unable to reestablish the subsystem whose failure triggered the fail-safe, the MAV will enter a landing sequence and touchdown. The return to base fail-safe mode is triggered by the following:

- Lost GPS signal
- Lost communication with the ground station

## 4.2 Immediate Withdrawal fail-safe mode

The immediate withdrawal fail-safe mode is designed to land the aircraft if the aircraft is unable to continue its mission or if it is unable to return to base. This fail-safe is triggered by multiple subsystem failure. When triggered, the autopilot commands a loiter for 5 seconds at its current location and then begins a fixed-pitch spiraling descent down to the ground. The 5 seconds allows a window for anomalous system input from the navigation or communications hardware.

## 4.3 Manual Override

When dealing with any novel or developing technology, unexpected behavior often occurs. Autonomous MAV flight is no different. To enable the ability to handle any anomalous behavior or system failures, a manual override has been added to the autonomous MAV system. Unlike the other fail-safe modes, this mode requires pilot intervention.

At any time during autonomous flight, the remote control (RC) pilot may bias the autopilot commands through the RC controller. This will not completely override the autopilot; it will only influence the control surface motion. If the RC pilot determines that the autopilot is no longer doing what it should, the pilot can enter the manual override mode, denoted Pilot-In-Control (PIC), by flipping a switch on the RC controller. With the system in PIC mode, the RC pilot has total control over the aircraft. If RC control is lost in conjunction with any other subsystem failure on the plane (GPS or communications) the aircraft will enter the immediate withdrawal fail-safe mode and begin a spiral descent and landing.

## 5 Conclusion and Expected Performance

The MAGICC Lab has a great deal of experience with small airplane autonomous flight, and the system we employ is proven over several years of use. All thought the competition this year is more demanding than in previous years, we look forward to meeting those challenges. We expect that our plane will fly autonomously for the duration of the mission and that it will quickly approach the targets. The main difficulty we foresee in the competition is accurately identifying the arches and plotting a flyable path through them.

Overall, we hope to be able to perform in a professional and impressive manner. We expect that we will learn a lot from the experience and that our system and expertise will grow from being under scrutiny. We hope that our system will perform consistently with the trials and tests we have put it through. We also hope that our love and enjoyment for robotic aviation shows through.

## References

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- [3] "Procerus technologies," 2006, <http://www.procerusuav.com/>.
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