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Test Bed Development for Shared Mission Autonomous Ground – Aerial Dissimilar Swarming: A Work in Progress Paper

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Abstract

Many researchers are currently focused on teams of near identical robots [1], this is called swarming or swarm robotics. This research area is based on the observance of swarms of insects that complete a significantly larger mission than any single insect could hope to accomplish alone. For example, the mounds built by ants, a beehive, or a hornet's nest. However, to most people all bees look the same, but from the bee's perspective, and the perspective of an entomologist, each bee hive is home to many different types of bees all with a job they are particularly suited for and assigned to. To truly mimic the swarming of insects, the robots in swarm robotics should be designed to complement each other and not necessarily be identical. To this end, this research aims to build up robots that are meant to work together on a shared mission, but that are far from identical. The mission to base the design of the robots around is discreet aerial surveillance and target identification with the ability to transport heavy loads and heavy artillery, a mission necessary to many military actions. To complete this research and test the developed strategies in the real world, the group has developed a teamed system concept as a test bed for this research. The system includes a robotic aerial quadrotor helicopter and a robotic ground vehicle with a weapon. The current mission under design is to allow the helicopter to identify the target and have the ground vehicle navigate to GPS coordinates identified by the helicopter, confirm the identification with its own vision system and "destroy" the target. For safety purposes the weapon is a paintball marker. This paper will discuss the test bed in its current stage, identify hurdles to success, and future directions for the research.

Introduction

Robotic swarming is a coordination approach to an autonomous mission that involves using multiple robots to work together in accomplishing a single goal. It is characterized by a collective behavior from the interactions of the robots with each other as well as their environment. The robots are often simple in design and functionality, but through their multitudes they obtain greater ability. The main focuses in swarming have been the physical characteristics of the robot and the controlling behaviors implemented as control algorithms.

Swarming has often been studied by observing the swarm intelligence that is inherent to the insects in nature. These studies often show that by creating simple individual rules inherent to each robot you can create complex behaviors within a swarm of robots. Each individual robot must constantly communicate and alter their behavior in order to react appropriately as a group. Often, in order to achieve a larger swarm, the individual robot must be simple so that it uses as few resources as possible. This can often force the focus of the accomplishment of the goal at the swarm level and not on the individual.

The many current applications of swarming technologies are categorized by the functionality and the control methods inherent to the individual robot. Each function will determine the application, but swarming in itself can take one function of the individual and create a new function as a whole. Control methods that have been used in the swarms hinge upon physical limitations and technological ability.

Currently, several teams of researchers are working to create some form of a swarm of robots to complete a mission. A team at the University of Southern California is working towards a bio-mimicry approach to the control of each member of the swarm by using what they call the Digital Hormone Method (DHM) [2]. Meanwhile their counterparts at the University of Karlsruhe in Germany seem less interested in mirroring the biology seen on earth as they are preparing a large team of centimeter scale robots to explore and colonize mars. While this team isn't using a bio-inspired control method they are taking advantage of a concept seen in nature that when one in the swarm is disabled the swarm continues [3]. Yet another team at the University of Essex, in the United Kingdom, are working on a "flock" of quadrotor helicopters they call Owls. Like the German group, the team in the UK considers the robustness of the swarm to be of utmost importance. That is, when one or even a few robots are disabled the swarm can continue with the mission. However, this group has taken the swarm a step further such that each member of the group shares its data and processing power with the others in order to not only work together but to think together as well [4].

While these three groups represent only a part of what is going on in the world when it comes to robotic swarming technologies, it gives a brief picture of the current focus in this area of research. All of these teams seem to have one thing in common; their swarm members are identical or near identical. On the other hand, we are working on using a group of dissimilar robots together as a kind of swarm. Just as in a beehive, most of the bees may look the same to us but from an entomological viewpoint the drone bees and the worker bees are outfitted very differently for their associated task. This approach allows us to take a mission further and accomplish larger goals such as a military action or a disaster site where debris has collapsed and people are trapped under it. In these scenarios, one robot type could squeeze their way into tight spaces to locate the trapped people or the hiding targets of a military action. Another, different robot can be designed to lift rubble to uncover the victims or engage the military target. If there was a swarm of locator robots and no robots design to actuate then it is likely that they, alone, would be unable to complete the mission. Attempts at making a team of similar, miniature robots with the capability to combine into something more capable is the only other alternative, but this option is likely more difficult.

This kind of tandem work approach with all types focused on one goal has excellent military applications. Our test bed is of a military operation consisting of seeking visually identifiable targets and destroying them. Using the mentality of multiple, identical member, swarms working as a "Great Swarm" one can employ not only robots capable of target identification and others capable of payload delivery, but one can have robots that collect specific intelligence, others that clear away impeding objects in the path, and still others that recover and repair their wounded counterparts. Each of the robots would be designed for just one specific function that would facilitate making a robot that is cheaper and smaller instead of many robots capable of doing everything themselves. This "Great Swarm" benefits from the uniqueness of each member swarm as well as the robustness of the individual swarm.

Mission and Test Bed

In order to accomplish the design of a robot team a specific mission is needed. To this end the team has designed the following mission and member identification as a target for the system design.

> To design and construct a Vertical Take-Off and Landing (VTOL) Quadrotor Helicopter (helicopter) and Autonomous Mobile Sentry Gun (sentry) such that the helicopter is capable of vertical take-off from the top surface of the sentry after human-specified GPS coordinates have been reached by the team. Furthermore, once the helicopter has lifted off it shall be tasked with locating a visually pre-defined target with the aid of its onboard vision system and wirelessly relaying GPS coordinates back to the sentry. The sentry will then carry out "target elimination" through the use of a paintball marker after visual confirmation from its own onboard vision system. During and after the mission the helicopter will be capable of landing back onto the sentry for battery recharging and theatre exit upon mission completion.

The Quadrotor Helicopter is an aerial vehicle that has recently come into interest in the robotic research community since battery technology has become inexpensive and light enough to power small scale aerial vehicles for relatively long periods of time between charges. Additionally, the popularity of hobby level remote control aerial vehicles has allowed some researchers the ability to enter this area given the economies of scale for parts that can be shared with the remote control community. From a research standpoint, the vehicle is highly desirable as a flight test bed mainly due to its inherent stability, given four points of thrust, and its relative ability to carry a small payload. While some current research focuses on the flight and aerodynamics of the Quadrotor Helicopter most recent research has been focused on the use of the flying vehicle once airborne. Much of this research [5-7] has focused on using vision systems on board the vehicle to identify objects below and to control the flight pattern of the vehicle. Helicopters are desirable over other forms of aerial vehicles for some tasks, such as surveillance, due to the ability to hover in a specific location.

A sentry gun is most commonly known in the computer gaming community because it represents more science fiction than it does commonly used military equipment. A sentry is a device that automatically senses the presence of an enemy, locates their position, and eliminates or disables them. Called the Phalanx CIWS, the first military use of a sentry was developed by Raytheon and first deployed in 1980 for the United States Navy. It uses an advanced radar system to locate and target potential enemies to protect a ship or fleet of ships from missiles or other weapons [8]. Another, more recent and on-going project taken on by the United States military is the Counter – Rocket, Artillery, Mortar (C-RAM) project. Since

1993, the C-RAM project has served the same function as the Phalanx CIWS system for land based protection [9].

While these two projects represent significant research, funding, and effort on the part of many constituents, the systems are not autonomously mobile. That is, they go were the ship does or are mounted on a stationary building and wait for enemy presence. In some cases it seems necessary to allow the sentry the ability to travel and seek out a target. This is the case, at least partially, in the ROBART program currently in its third phase of research [4]. The ROBART research program conducted by the SPAWAR Systems Center is currently operating under ROBART III and is capable of navigating a security pattern in confined spaces such as a warehouse. In this stage of development the vehicle fires rubber bullets or simulated tranquilizer darts at its identified enemy [10].

Currently, researchers are considering systems such as the Phalanx, the C-RAM, and ROBART III, but they seem focused on centralized sensing as opposed to remote or decentralized sensing which would require robot teaming or swarming. Decentralized sensing gives the mobile sentry the ability to understand the environment outside of its sensing range through wireless communication with other, different robots; robots designed to be the eyes and ears of the sentry. At this time it is not apparent that anyone is investigating the use of the Quadrotor Helicopter or any other aerial vehicle as a part of an autonomous robot team to complete shared missions with a mobile autonomous sentry or group of sentries.

The Mobile Sentry Design

The team has designed and built multiple sentry systems the first being remote-controlled to gain an overall picture of the issues presented by the platform. Shown in figure 1 is the current mobile platform in process. Currently, the platform is mechanically complete and functional but awaiting electrical controls.

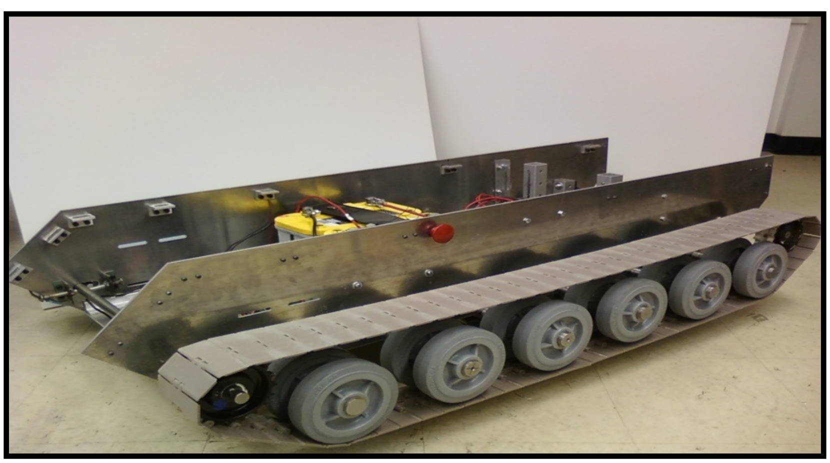

FIGURE 1: THE CURRENT PLATFORM

The platform is ~1500mm long, powered by a 24V 55Ah Lead-Acid battery through two 4.5Hp electric motors, and attains a top speed of ~1.2m/s. As the design for the control system is preliminary and untested, it will not be presented in this paper. However, the control system for the turret apparatus that is to mount on the top of the above platform is in testing stages and will be presented below. Figure 2 shows the turret assembly in its bench testing phase, before it is mounted in the platform.

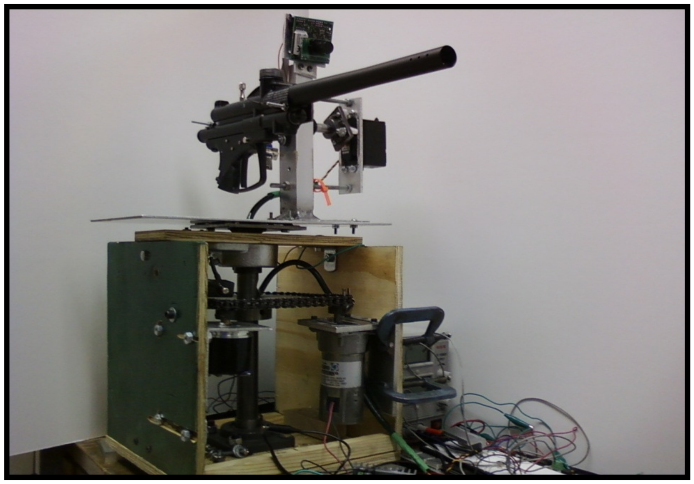

FIGURE 2: THE MOBILE SENTRY FIRING SYSTEM IN TESTING

The weapon, a semiautomatic paintball marker, is mounted such that the center of rotation coincides with the center of gravity to minimize the motor torque required to position and maintain a position. Because of the low level of required torque, the weapon elevation control was designed around a standard ¼" scale hobby servo motor. However, the turret rotation was too large to benefit from hobby level servo motors in an affordable range. Therefore, a custom servo system was developed for turret rotation. The system uses a standard DC motor and a shaft encoder for feedback. While they are mounted separately on a chain drive system they are each mounted with a sprocket of the same size to provide a feedback ratio of 1:1. The turret rotation is controlled with a standard digital PID loop and tuned using the Integral Square Time Error (ISTE) method. Not shown in figure 2 is another hobby level servo used for firing of the weapon. Figure 3 details the schematic of the system while Figure 4 shows the implementation of the PID control. Of great importance to the research being carried out is the fact that the entire system is controlled by an embedded system. This is the Propeller multi-core microcontroller from Parallax. This controller is a 80MHz microcontroller with eight cores and is available in a 40-pin DIP package, a 44-Pin QFN package, and a 44-Pin QFP package.

The PID controller has been implemented on a separate core of the microcontroller and uses tuned gain parameters of Kp = 27.486, Ki = 0.05, Kd = 0.309 and a 50mS integration time. The available encoder that has been implemented on this project is a 60,000 pulse per revolution encoder which is much more than necessary so the implemented counts has been divided down to 720 pulses per revolution. This provides a system that can be tuned in coarser increments. Furthermore, the encoder is not an absolute encoder so a home switch was installed that the system triggers against on boot and before entering the PID control loop. This home position is located just outside of the normal operating range. For obvious reasons the switch trigger position is considered 0 degrees while the operating range is 10 degrees through 190 degrees positioning the weapon a full 180 degrees; 90 degrees to the left and right of the forward position.

Because the weapon elevation is handled by a standard servo motor, the implementation is quite simple. A standard servo motor responds to a pulse sent out in 10-20mS cycles. The pulse width determines the motor position that is traveled to and held. The maximum and minimum weapon elevation angles are associated with pulse widths of 1.4mS and 1.8mS respectively. The range of the elevation is 45 degrees above parallel and 15 degrees below parallel.

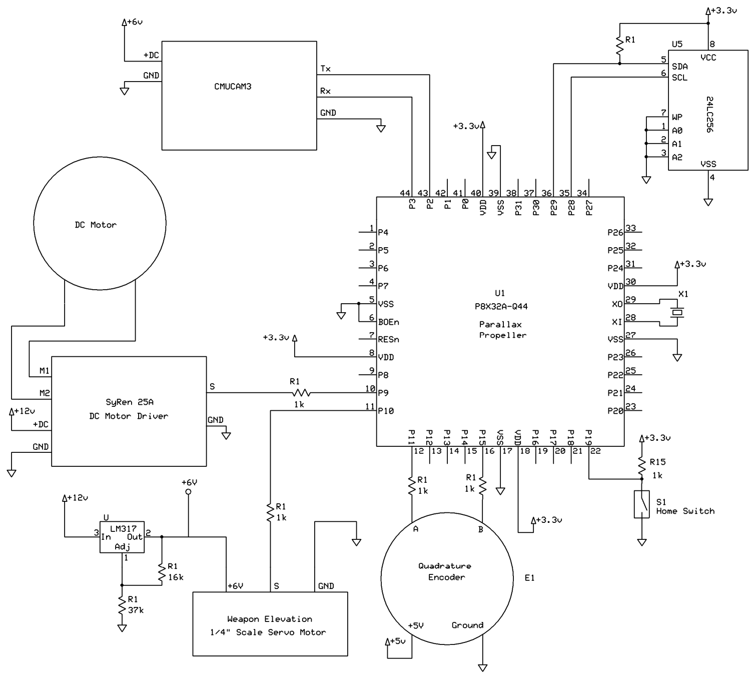

FIGURE 3: THE TURRET ASSEMBLY SCHEMATIC DIAGRAM

```
PRI Loop | P, I, D, cur_error, pre_error, W, count, CP

  I := 0.0                                              'Initialize the integral variable.
  W := F.FTrunc(F.FMul(80_000_000.0,dt))                'Calculate iteration time in clock cycles.
  repeat                                                'repeat indefinetly.
    count:=cnt                                          'Store the system clock.
    CP := (F.FDiv(F.FFloat(long[cur_pos]),83.33))       'Obtain the current position.
    cur_error := F.FSub(F.FMul(2.0,long[set_pos]),CP)   'Determine current error.
    P := cur_error                                      'Calculate the Proportional part of the output.
    I := (F.FAdd(I,F.FMul(cur_error,dt))<# 80.0) #> -80.0 'Calculate and limit the Integral part of the output.
                                                        'to prevent integral windup.
    D := (F.FDiv(F.FSub(cur_error,pre_error),dt)<# 80.0) #> -80.0
                                                        'Calculate the Derivative part of the output.
    pre_error := cur_error                              'Set the previous error equal to the current error.
    long[output] := (F.FRound(F.FAdd(F.FAdd(F.FMul(P,Kp),F.FMul(I,Ki)),F.FMul(D,Kd)))<# 255) #> -255
                                                        'Calculate and limit the total output.
    MC.tx(F.FRound(F.FDiv(F.FAdd(F.FFloat(long[output]),255.0),2.0)))
                                                        'Normalize the output around 127(motor stopped).
    waitcnt(W + count)                                  'Wait the remainder of the iteration time.
```

FIGURE 4: PID CONTROL IMPLEMENTATION

In figure 4, the implementation of the PID loop is shown. The propeller microcontroller does not have built in floating point capabilities so it has been constructed using an IEEE 754 technique. Therefore, when two numbers need to be multiplied together the resulting code is F.FMul(A,B) as the floating point math is completed by an object file with the 'F.' identifier. Additionally after the total controller effort has been calculated, the output (ranging from -255 to 255) must be shifted to range from 0 to 255. To the motor controller, 0 is full speed reverse and 255 is full speed forward while 127 is stop. The motor controller is setup in serial communications mode so the MC.tx command simply transmits out a byte of data representing the controller effort by another object file.

Once fully implemented the results of the tuned PID rotation control are shown in figure 5.

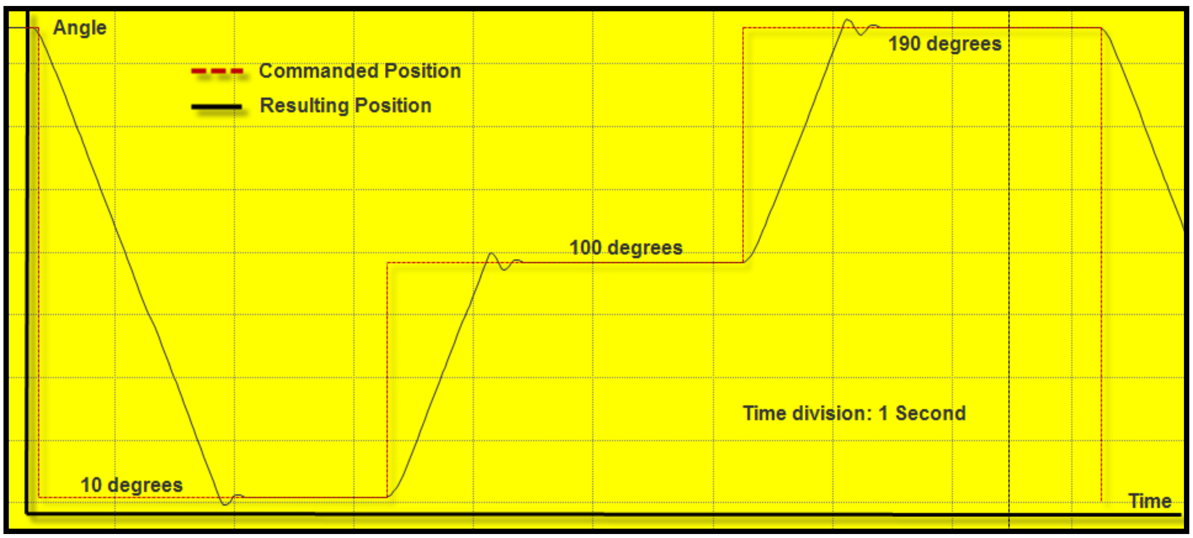

FIGURE 5: PID CONTROL RESULTS DURING TUNING TEST

One interesting note is the response overshoot and oscillation when the angle increases is larger than when the angle decreases. This is due to the fact that the system is chain driven and the sprocket alignment is not perfect given the bench top test setup nature of the system. It is expected that once the system is mounted inside the mobile platform that the response from an increase will be closer to that of the response to decrease. When it is remounted the system will likely require re-tuning.

Of course, when the system is in operation it will not look like the tuning test results shown above. This is due to the control being performed based on the results provided by the camera system mounted on the weapon rotation mast. The camera used in the system is the CMUCAM3 by Carnegie Melon University. Previous versions of this device have effectively been black boxes with a command set including such things as blob detection and color detection. Version 3 gives the designer access to the internal code and is therefore considered an open-source device. This allows more of the vision algorithm to exist on the camera and removes a significant part of the processing burden from our microcontroller. At the time of writing the CMUCAM3 code is under development and near completion. The camera software is designed to return the center of mass and the blob size of a prescribed color (dark red) representing the desired target. Because the turret rotation also moves the camera we have a 180 degree angle of view plus the inherent angle of view of the camera.

However, since the weapon elevation system does not affect the angle of the camera, the weapon will be pitched to an angle dependant on the center of mass of the identified target in the vertical dimension taking into account projectile physics. Based on the area of the identified blob and given a known target size, the distance to the target can be calculated and used to consider projectile drop. Before firing, the turret will center the target in the view of the camera and pitch the weapon angle.

THE HELICOPTER DESIGN

Designs and control approaches on the Quadrotor were studied from research at the Australian National University, Stanford, The Swiss Federal Institute of Technology, Pennsylvania State University, Brigham Young University, and the University of Cambridge to name a few [11-17]. Based on the results of these other teams we have designed the helicopter.

Figure 1: Photograph of the Helicopter

For the same reasons as in the sentry, all computing is completed onboard the aircraft via four multi-core microcontrollers yielding 32 independent computing units. Each of these microcontrollers has a specific task. The first of the microcontrollers, the IMU Microcontroller receives data from the onboard inertial measurement unit and communicates roll, pitch, and yaw to the ZIGBEE Microcontroller. The ZIGBEE Microcontroller also receives communications from the GPS Microcontroller which includes GPS data, battery voltage data, and temperature data. Additionally, the ZIGBEE Microcontroller collects altitude information from a downward looking sonar sensor. The ZIGBEE Microcontroller then communicates roll, pitch, yaw, battery voltage, temperature data, and GPS information to the MOTORS Microcontroller and transmits monitored data to the base station via a zigbee wireless transceiver where it is displayed on a monitoring television for safety and development purposes. The MOTORS Microcontroller uses the sensed and filtered data to determine the commanded motor speed for each of the motors. The MOTORS Microcontroller contains several PID loops, each operating on their own core to maintain a low iteration time. Currently, three of the loops have been implemented almost identically to figure 4. These loops control the roll, pitch, and altitude.

Communications

The wireless communication chosen for the system is Zigbee. The choice to use a low data rate, short-range communication protocol was certainly purposeful. In many current military situations cell phones and other personal devices are being used to trigger Improvised Explosive Devices (IED) because these devices are readily available, comparatively cheap, and the signal is reliable. If the system described herein relied on Bluetooth, Wi-Fi, or another comparative technology the individuals representing the targeted location could use a readily available device to break into the network, even with security measures, and intercept device-to-device transmissions. For example, many cell phones and other personal devices have Bluetooth and Wi-Fi capability but not typically Zigbee. In a future design, the wireless protocol used would likely be custom and utilize the latest anti-jamming and high-reliability technology, but since this research is not about wireless communications the team chose to implement the best technology currently available and reasonably affordable.

Another piece of the design that will not likely exist in a future design is the base station monitor. This consists of a single microcontroller, a Zigbee device, a keyboard, and a display device. This functions as the Command Center of the system and allows a full running view of both systems on one screen. This includes battery voltages, sensed temperatures, GPS locations, IR and sonar sensed values, IMU values, and weapon rotation and pitch angle values. The keyboard allows control of certain parameters in the system during the various testing phases but is not designed to be a remote control station.

Conclusions and Future Direction

Each day we progress further towards our goals and come closer to realizing the benefits a capable robot team can provide to the world around us. With military actions around every corner and governments wishing to put fewer soldiers in harm’s way, a machine driven solution is the ultimate goal. With the “Great Swarm” described herein, a military action could be carried out by machine alone instead of soldiers, still in harm’s way, using a remote controlled “robot” designed to minimize harm to the soldiers that operate them instead of completely remove them from the situation. Of course, with these technological advances comes numerous societal concerns regarding a robot revolt and other societal impacts that the automation of warfare has [18].

At the time of this writing the team is engrossed in the development of the sentry and the quadrotor. Test flights have been completed and control loop tuning is under way on the quadrotor system while programming is underway on the sentry. For the sentry, some of the system level components have been programmed and tested including the IMU components, weapon pitch and rotation, GPS, and the motor controller communications. For the quadrotor, programming is near complete. Further research is required but a camera system is planned for the Quadrotor such that it can “see” and locate the targets from the air. We expect that we will have a working relationship between our dissimilar swarm members by early summer 2011 and hope to achieve mission completion late in the fall of the same year.

Once the single pair is complete and we are able to test them through mission completion, we aim to duplicate the individual devices so that we can closer imitate swarming behaviors within like designs. For the future we will continue to improve upon designs and focus on the common characteristics needed to be instilled within each member of all different swarms. These common behaviors are the key to having a swarm act appropriately to accomplish a greater goal. Without these common behaviors we cannot truly call it a "Great Swarm."

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Biography

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