Design and Development of South Dakota School of Mines and Technology's Aerial Robotic Reconnaissance System

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ABSTRACT

The South Dakota School of Mines and Technology Unmanned Aerial Vehicle Team will participate in the 2009 International Aerial Robotics Competition with a single quadrotor helicopter. The vehicle has been designed to autonomously locate and enter a one square meter opening, traverse a series of obstacles in search of a control panel, and transmit live video of the target gauge to an operator control unit. To achieve the desired level of autonomy, a Simultaneous Localization and Mapping algorithm and an Extended Kalman Filter provide a state estimate for a Fuzzy Logic flight controller. Communications between an onboard embedded computer and an operator control unit meet Level 2 JAUS compliance.

1 INTRODUCTION

1.1 Problem Statement

The goal of the International Aerial Robotics Competition (IARC) is to complete an indoor reconnaissance mission using an autonomous aerial robot. To assist with goal development, the team divided the mission into three critical stages. Stage 1 begins when the vehicle is on the ground and concludes with successful ingress of a one square meter opening. Stage 2 requires the aerial robot to traverse the corridors and rooms of the building in search of the control panel. Stage 3 requires the robot to identify the correct gauge on the control panel marked by a solid blue LED. The vehicle will ensure the gauge remains in the video image for at least five seconds. Completion of the mission occurs when the judge observes the value on the gauge as displayed on the operator control unit (OCU).

1.2 Conceptual Approach

The South Dakota School of Mines and Technology Unmanned Aerial Vehicle (SDSM&T UAV) team has devised a quadrotor helicopter capable of completing the 2009 IARC mission. The vehicle concept is a result of extensive analysis of the team's previous designs from the third stage of the 2007 and 2008 IARC competitions. Upgrades to the onboard electronics and a broader understanding of flight control concepts have allowed the progression of the Structure Entry and Reconnaissance Vehicle (SERV) to move forward into its current state.

The SERV will begin on the ground at a distance of 3m from the building and oriented toward the one square meter opening. Once the opening to the building is located, the quadrotor will enter into a corridor to begin its search for the control panel. The flight controller will avoid obstacles and guide the robot to the room with the target. Video data will be transmitted from the vehicle and recorded by the operator control unit. A Simultaneous Localization and Mapping (SLAM) algorithm will generate a global map of the vehicle path and environment. Positional commands generated by a planning algorithm on the OCU will be sent via 802.11g wireless to the vehicle to be executed. Once the control panel is identified, the SERV will track the gauge marked with a solid blue LED for a minimum of five seconds. The overall system architecture is illustrated in Figure 1.

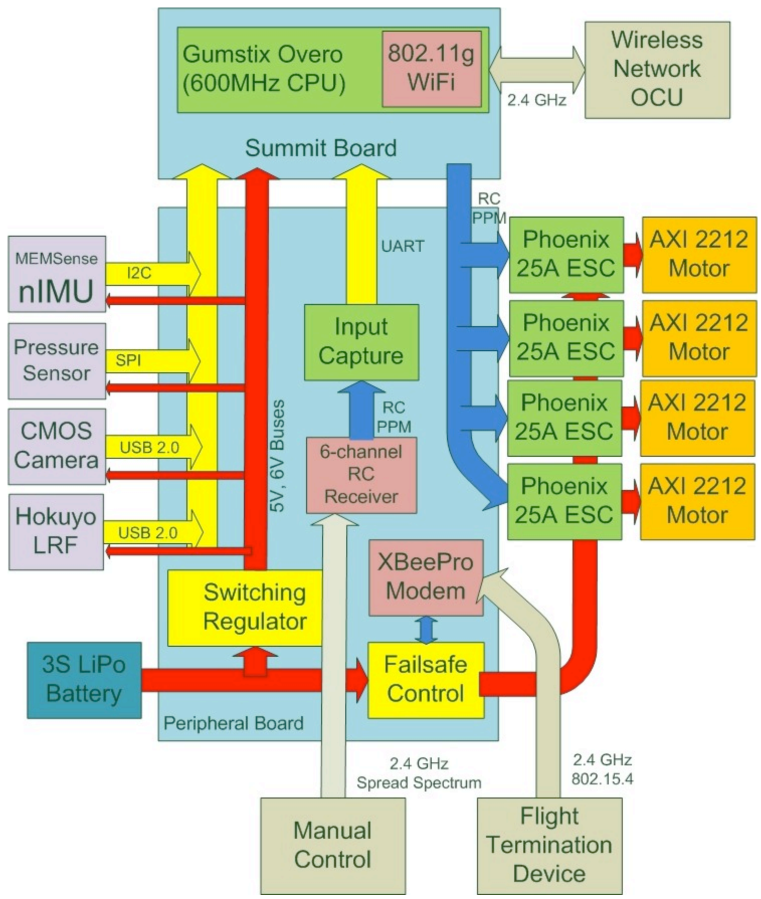

Figure 1. Overall System Architecture

1.3 Yearly Milestones

Following the previous year's competition milestones, the team has taken its design of the SERV to a new level. An improved airframe has been developed to reduce weight, increase flight durability, and improve operational safety. Additionally, a motor test platform was developed to examine the characteristics of prospective motor and propeller configurations. A flight controller designed specifically for indoor navigation and reconnaissance has been under development with significant progress made in the last year. A focus on a complete model-based control design has led to successful implementation of an Extended Kalman Filter (EKF) in conjunction with a SLAM algorithm. The team's focus on research and knowledge transfer between students has resulted in the development of an online wiki server complete with team documentation, source code, and forums. With design architectures focused on efficiency and systems integration, the team is forging ahead to complete the 2009 IARC.

2 AIR VEHICLE

2.1 Propulsion and Lift System

The SERV is a Vertical Take-off and Landing (VTOL) vehicle consisting of four brushless DC motors turning four fixed-pitch propellers. The motors and propellers are oriented in two counter-rotating pairs in an X-configuration and mounted to a laminated composite airframe structure. The center of the airframe contains the avionics bay, which houses all of the onboard electronics. The airframe also incorporates composite shielding around the propellers to prevent them from contacting any obstacles during flight. Figure 2 illustrates a Solidworks model of the SERV.

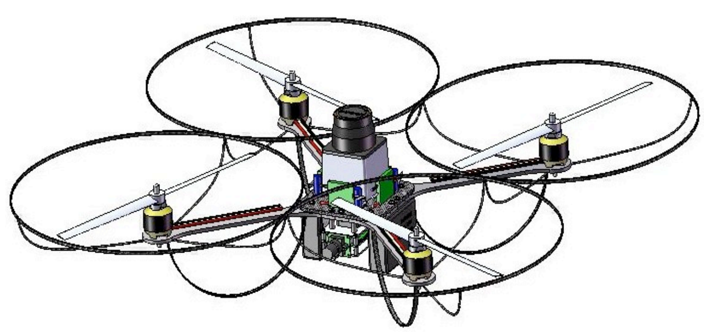

Figure 2. CAD Model of SERV

A motor test platform was developed to thoroughly test and analyze the propulsion system and to determine the optimal combination of commercial off the shelf (COTS) components. The AXI 2212-34 brushless motor with a two-bladed APC 10x4.7 propeller is the best combination for the competition size and weight constraints. The operation of the motor test platform is explained in more detail in section 5.4. This single motor and propeller configuration is capable of producing 600 grams of thrust at 7500 RPM while drawing 8.25 amps. The total weight of the SERV is approximately 1000 grams.

2.2 Guidance, Navigation, and Control

Autonomous navigation and control is achieved via an autopilot system consisting of integrated COTS hardware and custom flight control algorithms. This system allows the flight path to be autonomously altered in real time in response to inputs from onboard sensors. Sensors include a MEMSense nIMU inertial measurement unit, a Mobisense Systems Aptina MT9V032 CMOS camera, a MEMs SCP1000 pressure sensor and a Hokuyo model URG-04LX scanning laser range finder. An EKF is implemented in conjunction with a SLAM algorithm. Sensor measurements, together with the position and orientation estimates from the SLAM algorithm, are fused using the EKF. The Kalman Filter provides an estimation of the vehicle state. Navigation is accomplished with a path planning algorithm which generates flight commands based on the current state estimation. A fuzzy logic controller performs the attitude and position control while maintaining the stability of the quadrotor in hover and translational flight.

2.2.1 Stability Augmentation System

The stability of the UAV is maintained by the flight controller which consists of a Gumstix Overo Fire embedded computer running Debian Linux, and a MEMSense inertial measurement unit. The flight controller utilizes fuzzy logic control to manage hover and translational flight. The SLAM and path planning algorithms are primarily used to maintain course and position relative to obstacles.

2.2.2 Navigation

The autopilot navigates the quadrotor through rooms and corridors in real time based on the fusion of immediate sensor measurements. The scanning laser range finder provides the path planning algorithm with measurements of range and bearing to obstacles. Simultaneously, the vehicle state is updated locally on the embedded computer and transmitted to the OCU where a global map of its surroundings is coalesced. Hence, an estimation of the vehicle location with respect to immediate surroundings is formed. Navigational commands are generated on the OCU and executed by the vehicle flight control system. In this manner, navigation, localization, and mapping are accomplished simultaneously and efficiently with the majority of the computational budget being allocated to the OCU. Figure 3 illustrates the control system architecture.

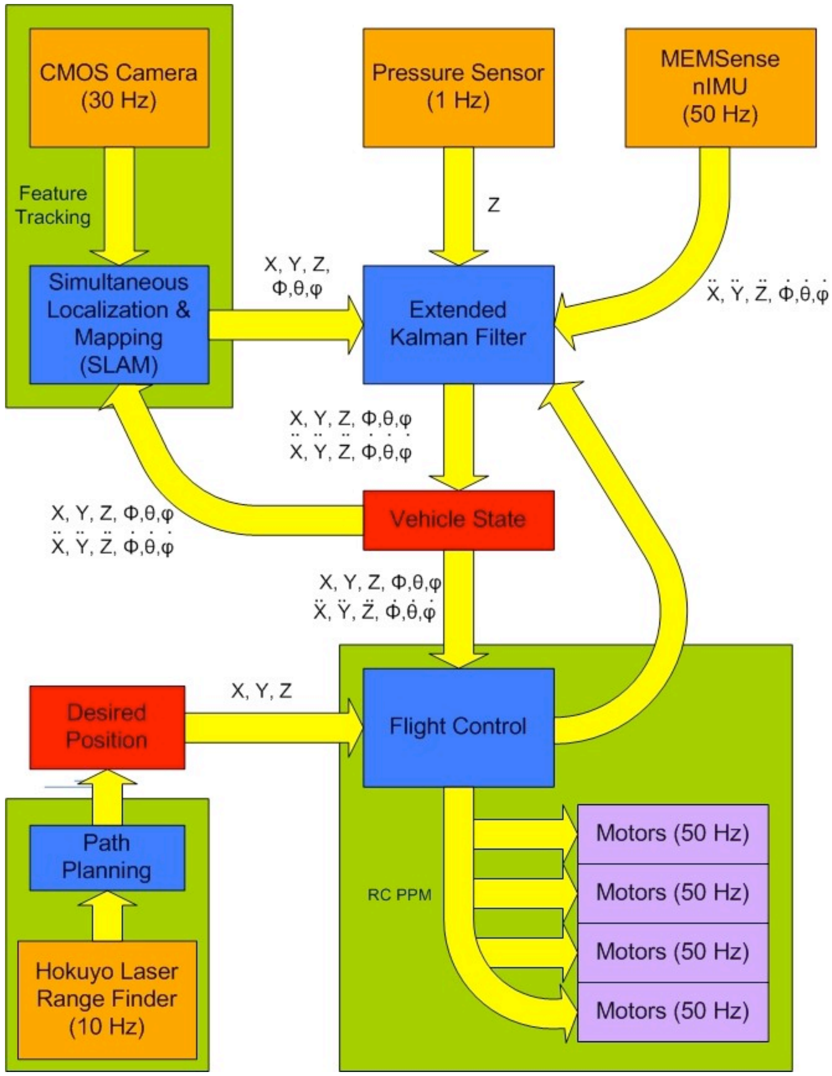

Figure 3. Control System Architecture

2.3 Flight Termination System

The flight termination system for the SERV consists of a remote activation switch and an onboard failsafe circuit. The remote switch is battery powered and transmits via a 2.4GHz XBeePro radio module. A matching radio module on the vehicle controls the failsafe circuit. When the remote switch is activated, the radio modules drive a control line in the failsafe circuit, allowing current to flow from the vehicle's battery to the motor electronic speed controllers (ESC). If the remote switch is deactivated or the vehicle goes out of range, the failsafe circuit will immediately cut power to the ESCs and render the vehicle ballistic.

3 PAYLOAD

3.1 Sensor Suite

The SERV carries several sensors onboard whose outputs constitute the inputs to the control system, thus allowing autonomous flight to complete specific tasks required by the IARC. Data is processed onboard by the Gumstix computer and simultaneously relayed wirelessly to the OCU for further processing. The Gumstix Overo is an embedded motherboard using the Texas Instruments OMAP 3530 series microprocessor, and the OCU is a commercially available Lenovo laptop computer operating Linux.

3.1.1 GNC Sensors

A MEMSense inertial measurement unit containing three accelerometers, three gyroscopes, and a three-axis magnetometer serves as the vehicle's primary sensor package. A Mobisense Systems Aptina MT9V032 camera module provides image data for use by the SLAM algorithm and for display on the OCU. A MEMs SCP1000 pressure sensor provides an altitude estimate in addition to the estimate provided by the SLAM algorithm. A Hokuyo model URG-04LX scanning laser range finder estimates range and bearing to environment obstacles. The range and bearing data are used by the path planning algorithm to avoid immediate threats.

3.1.2 Mission Sensors

The Mobisense CMOS camera is used to identify and locate the opening to the building, the control panel, and the target gauge. In addition, the mission sensors aid in guidance, navigation, and control as outlined in section 3.1.1. The OCU software uses the mission sensors along with the guidance, navigation, and control sensors to complete all the requirements of the mission.

3.1.2.1 Target Identification

Target identification is crucial to the completion of the IARC mission. The first target that will need to be identified is the one square meter opening to the building. This will be done with a feature tracking and SLAM algorithm combined with range data from a Hokuyo scanning laser range finder. While navigating the building, a algorithm will be used to identify the solid blue LED on the control panel. Once the solid blue LED is located, the flight controller will alter the vehicle position to ensure the blue LED is in the bottom half of the video frame, thus allowing the target gauge to be within the field of view of the camera.

3.1.2.2 Threat Avoidance

The Hokuyo scanning laser range finder functions as the SERV's primary means of threat avoidance. The SLAM algorithm generates a global map of the vehicle's environment and path including obstacles that have been identified and tracked. The planning algorithm utilizes the obstacle range and bearing data along with the global map to plan the path of the vehicle and generate navigational commands. In addition, if the laser scanner senses an immediate threat during execution of position commands, the planning algorithm will immediately alter the vehicle's motion thereby intelligently avoiding a collision.

3.2 Communications

The Gumstix Overo Fire module is capable of communicating via Bluetooth as well as Wifi. Given the data quantities and needed range, the performance of 802.11g best meets the requirements of the mission. For these reasons, the system uses the WiFi module to communicate the necessary state and sensor information between the vehicle and the OCU. A Buffalo 2.4GHz wireless router is used to relay data to and from the OCU. A link margin analysis proved that this communication system will broadcast to 100 meters reliably in the presence of 6dBm of building structure attenuation. Video data will also be transmitted over WiFi.

The flight termination system, however, uses a separate XbeePro 2.4GHz module, which sends the interrupt command to the onboard flight termination circuitry. The XbeePro module also meets the requirements for the link margin.

The SERV communication system fully obtains Level 2 JAUS compliance. All messages passed between the UAV, OCU, and common operating picture (COP) meet the JAUS standards. While the system is compliant as verified by the JAUS validation tool, a more robust communications package is under development to further achieve the goal of complete JAUS interoperability between multiple vehicles and all of their components.

3.3 Power Management System

The SERV power system is comprised of two identical Thunder Power 2000mAh, 16C, 11.1V, lithium-polymer batteries wired in parallel. The batteries weigh a combined 254 grams with connectors. The SERV draws approximately 21 amps while in a hover, requiring at least 4000mAh total in order to achieve ten minutes of flight time. The vehicle is equipped with four AXI 2212-34 brushless motors, which are powered by four

Castle Creations Phoenix 35 electronic speed controllers. The remaining electronics on the SERV, including the Gumstix computer and the GNC sensors draw power from the same two batteries. Power consumption was a critical factor in the selection of these components and was also taken into consideration when selecting the batteries for the vehicle.

4 OPERATIONS

4.1 Flight Preparations

Prior to any flight, several tasks are to be performed to ensure successful flight operations. Team members are assigned duties for which they have been trained. A safety briefing is held prior to each flight, which is outlined in section 5.2. A flight operations briefing covers the flight plan and defines vehicle behavior, which may necessitate emergency procedures. This briefing concludes with a question and answer period. This type of format has been successful in keeping the team and all observers safe and informed on the events of the flight.

4.2 Checklists

The team follows a set of checklists for its pre-flight, launch, and post-flight procedures. These checklists cover the systems vital to flight and sensor navigation. A flight plan, which outlines the goals and exceptions, is generated before each flight. Flight characteristics are recorded in a flight log. The checklist and log entries must be completed before proceeding with the next flight.

4.3 Man/Machine Interface

The SERV can be flown manually or autonomously. When flying in manual mode, a standard R/C transmitter is used to control the quadrotor. There are two different autonomous modes. Autonomous mode one allows full computer automated control of the quadrotor. When this mode is initiated, the helicopter will be working toward accomplishing the three stages of the competition as defined previously in section 1.1. When in autonomous mode two, commands can be sent from the graphical user interface (GUI) running on the OCU to guide the helicopter in its surroundings. The operator is able to monitor all mission critical data through this interface while simultaneously operating the SERV in autonomous mode two.

5 RISK REDUCTION

5.1 Vehicle Status

The mission status for the SERV is observed through the OCU. Vital flight data is displayed in real time to illustrate the vehicle status while it is simultaneously recorded to allow for post flight analysis. Flight data includes camera video data, vehicle attitude, vehicle altitude, battery voltage, communication signal strength, and SLAM navigation solutions.

5.1.1 Shock/Vibration Isolation

Shock loadings and high frequency vibrations are of major concern for flight operations of any VTOL aircraft. The most common scenario for shock loading arises during a hard landing. The landing gear for the SERV has been designed to dissipate energy in the event of a hard landing, thus protecting the electrical hardware and the airframe. High frequency vibrations can lead to fatigue and premature failure of mechanical and electrical components along with erroneous sensor readings. The brushless motors and propellers will be spinning in excess of 7500 RPM, causing the majority of the forced vibrations into the system. Design considerations have been taken to ensure that these high frequency vibrations are not transmitted to the electronic hardware.

5.1.2 EMI/RFI Solutions

The team has given considerable thought to the effects of EMI/RFI on the vehicle's electronic and communications equipment. Communication failures and system problems have been experienced in the past, and were attributable to interference generated by onboard components. Although these issues have been largely resolved, efforts are ongoing to identify sources of EMI/RFI and eliminate or attenuate any negative effects. Shielding techniques have been utilized wherever possible, and sensitive components such as the MEMSense nIMU have been located farthest from noise producing components. Troublesome devices have been eliminated wherever possible, and any new components introduced are scrutinized for EMI/RFI issues.

5.2 Safety

The airframe has been designed to incorporate physical shielding around the propellers to protect the airframe and any nearby personnel during flight operations and testing.

The team has established procedures to ensure safety during flight-testing operations. A safety briefing is held prior to any flight during which any hazards or threats and appropriate responses are discussed and clarified. Team members are also trained on the pre-flight, launch, in-flight and post-flight procedures. In particular, the use of the flight termination switch and its implications are emphasized in training. In order to become a certified pilot, team members must spend the required time practicing on the simulator and under supervision before a final performance evaluation is conducted. All flight tests, conditions, and results are recorded in the flight logbook, along with any routine maintenance performed on the vehicle. The team uses a red tag system to mark damaged or malfunctioning components so that defective equipment is not used until the appropriate repairs have been completed. Additional safety training is provided for general laboratory safety and lithium polymer battery charging.

5.3 Modeling and Simulation

A non-linear, six degree-of-freedom, state-space model of the vehicle was developed. The modeled quadrotor kinematics and dynamics include motor torques, body forces, body torques, mass moments of inertia, gravity forces, and Coriolis effects. The dissymmetry of lift with radial propeller location and vehicle orientation was simulated in Matlab and included in the full model. Factors that were neglected in modeling of the vehicle include aerodynamic effects induced during rapid ascent and descent. In addition, blade flapping was assumed negligible due to the design selection of rigid, fixed-pitch propellers.

In the model, state variables include inertial 3-axis positions, velocities, rotational angles, angular rates, and accelerations. The model was utilized in extensive Matlab and Simulink simulations of the system and in development of the state-based fuzzy controller. Research continues on model-based control with development focused on a linear quadratic regulator (LQR). The inertial model is directly used in conjunction with an EKF to produce the full state estimation.

Solidworks was used to complete a 3-D CAD model of the SERV. Mass and material properties were defined and a weight budget was used to accurately characterize the thrust to weight ratio of the SERV. Mass moments of inertia (MOI) of the vehicle about the three body axes were experimentally measured using a bifilar pendulum test stand and subsequently verified with MOI estimates from Solidworks. Motor torques and thrusts were also experimentally measured using a motor test platform.

5.4 Testing

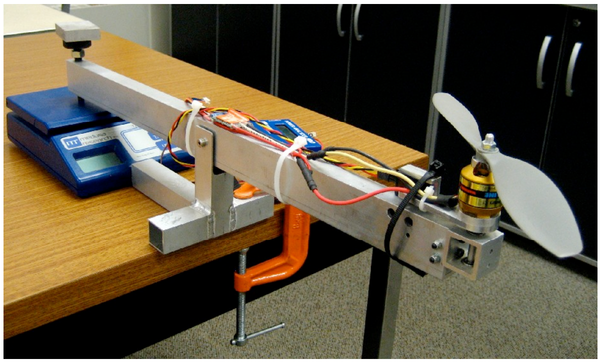
Figure 4. Motor Test Platform

As mentioned in Section 2.1, the team designed and manufactured a motor test platform as illustrated in Figure 4. The testing apparatus has an aluminum frame and is similar in design to a well-balanced lever on a fulcrum. The motor is mounted at one end of the frame and a counter-weight is placed at the other end with a thrust measuring device underneath. The motor test platform also incorporates COTS brushless motor testing software and accompanying hardware package from Medusa Research. The Medusa Power Analyzer Pro includes sensors and a data acquisition unit to measure the motor thrust, RPM, and electrical parameters. The software displays and records the motor test data using a PC.

Test data from five brushless motors and ten propellers was collected and analyzed. Figure 5 illustrates three combinations of motors and propellers. The final selection was based on the most efficient combination for lifting an expected payload of 800 to 1500 grams. A load cell was designed into the motor test platform to measure the reaction torque of the system. These measurements were then used in the vehicle modeling for flight controller design.

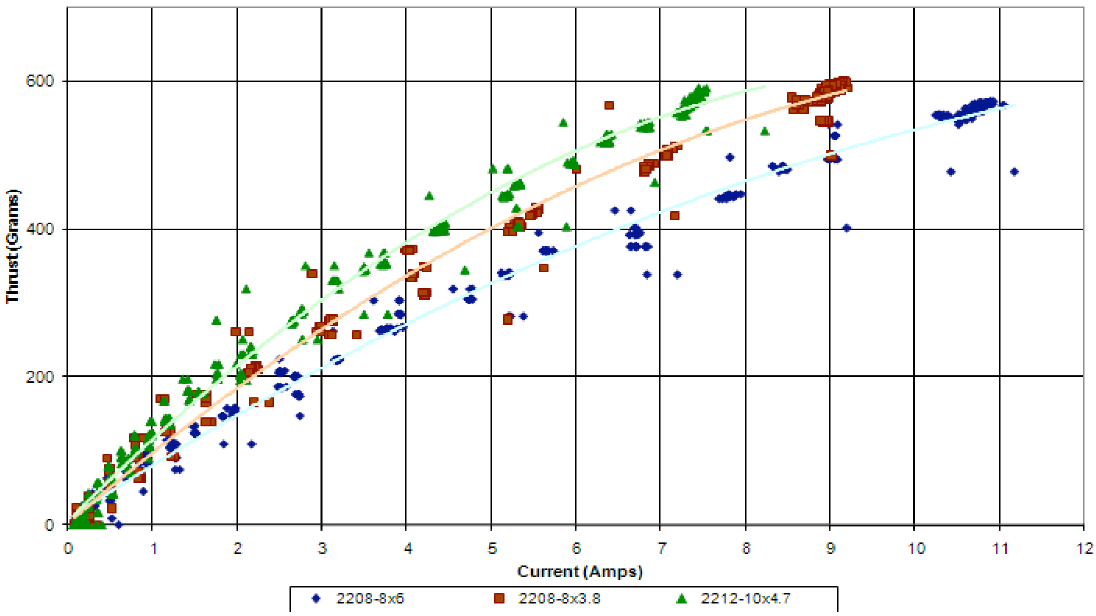

Figure 5. Thrust vs. Current Plot

6 CONCLUSION

The SDSM&T UAV team has developed an autonomous quadrotor capable of locating and entering a one square meter opening, traversing a series of obstacles in search of a control panel, and transmitting live video of the target gauge to an operator control unit. In this manner, the SDSM&T UAV team intends to complete the fifth IARC mission in its entirety. The integrated design of the SERV will allow the completion of the mission while demonstrating the possibility for other applications such as disaster relief, surveillance, and reconnaissance.

7 ACKNOWLEDGEMENTS

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