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 (SDSM&T UAV) Team will participate in the 2010 International Aerial Robotics Competition (IARC) 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 to obtain and replace a USB flash drive with a mechanical arm actuated by a servo. This is to be done within ten minutes while avoiding detection from devices such as cameras and laser barriers. To achieve the desired level of autonomy, a monocular Graph Simultaneous Localization and Mapping (SLAM) algorithm along with the vehicle's attitude estimation will provide estimates of the vehicle's location as well as a map of the environment. Communications between an onboard embedded computer and an operator control unit meet IARC Joint Architecture for Unmanned Systems (JAUS) compliance.

1 INTRODUCTION

1.1 Problem Statement

The goal of the 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 while the blue LED above the opening is off. Stage 2 requires the aerial robot to traverse the corridors and rooms of the building in search of the Chief of Security's office. Stage 2 also consists of avoiding all obstacles and the laser barrier. Stage 3 requires the robot to identify and pick up the target flash drive, after which it will drop off a dummy flash drive. Once the flash drive is secure and the dummy flash drive is dropped off the vehicle will then exit the building. Completion of the mission occurs when the judges receive the target flash drive.

1.2 Conceptual Solution

The SDSM&T UAV team has purchased a MikroKopter M3-ME Quadkopter to assist in the completion of the IARC. This vehicle will provide robust attitude control along with the framework to expand the hardware, software, and sensor suite to complete the requirements of the IARC. The vehicle concept is a result of extensive analysis of the teams previous designs from IARC competitions. Upgrades to the onboard electronics and a broader understanding of flight control concepts and path planning algorithms 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 three meters from the building and oriented toward the one square meter opening. It will then rise into a hover in order to locate the building's opening. Once the opening to the building has been found the SERV will loiter in order to detect the blue LED. An onboard camera is used to send video data to the OCU to run a feature detection algorithm that detects the blue LED, the building opening, and other obstacles within the building. Once the blue LED is detected, the quadrotor will loiter until the LED shuts off. If the LED has been determined to be off, the quadrotor will progress into the corridor to begin its search for the flash drive.

A path planning algorithm running on the OCU determines desirable paths to navigate the vehicle in ways that avoid obstacles, disengage the laser barrier, and guide the robot to the room with the target. The path planning algorithm uses data describing the environment from a GraphSLAM algorithm on the OCU. The SLAM algorithm also generates the location and historical path of the vehicle within this environment. The position commands generated by the path planning algorithm are sent from the OCU via 802.11g wireless to the vehicle to be executed on the MK Navi Controller.

After ingression of the building has begun the SERV will then search for the flash drive. Once the flash drive is identified using feature detection, the SERV will hover next to the inbox, extend a robotic arm, pick up the flash drive and release the dummy flash drive. When this operation is completed successfully, it will exit the building while still avoiding all obstacles, laser barriers, and video detection devices. The overall system architecture is illustrated in Figure 1.

1.2.1 System Architecture

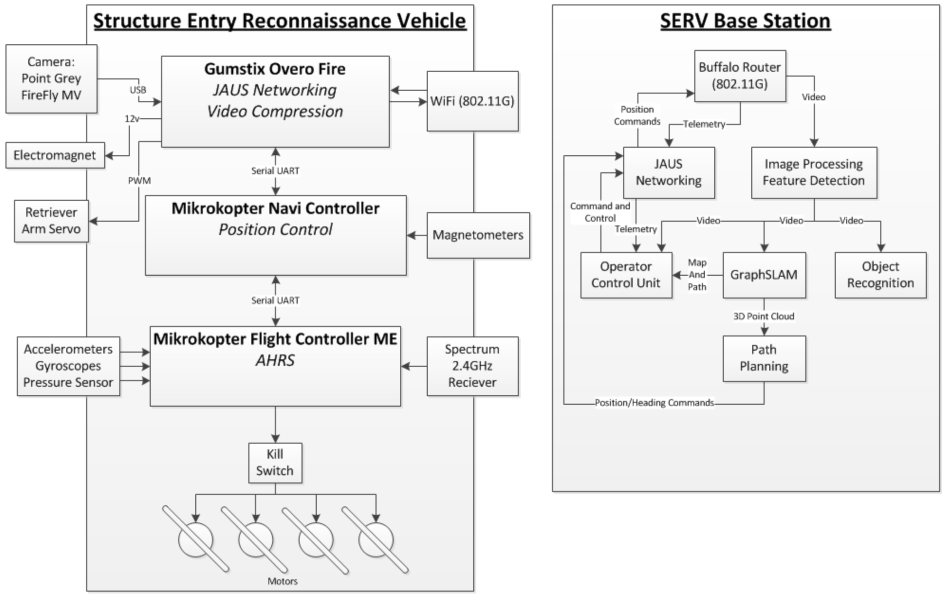

Figure 1: *2010 SDSM&T System Architecture*

1.3 Yearly Milestones

Following the previous year's competition milestones, the team has taken a different path in the development of the SERV. Development of SDSM&T's custom airframe has continued, but research in commercial quadrotor vehicles has been the focus. The commercial off the shelf (COTS) vehicles that have been extensively tested are from Draganfly Innovations and MikroKopter. There are also future plans to research the Ascending Technologies Pelican. The team decided to pursue the MikroKopter Quadrotor because of its robust and stable attitude heading reference system (AHRS) along with ability to easily adapt and integrate components to the vehicle. The team has also continued research in vehicle modeling through various test stands for system identification and controller development.

The main developments have come in the form of monocular GraphSLAM, path planning, and position control. The team's GraphSLAM algorithm is based off of Ethan Eade's work at Cambridge University [2] which was then implemented and optimized by a Computer Science senior design team from SDSM&T. The UAV Team is working on a path planning algorithm that will read in a 3D point cloud of the vehicle's surroundings as well as the location of the vehicle provided by GraphSLAM and develop a map, points of interest, and coordinates for the vehicle to follow. The coordinates are then read into the MK Navi Controller board for vehicle translation. The MK Navi Controller board is part of the COTS MikroKopter airframe and it contains the position controller and a serial interface for development.

A senior design team consisting of three Mechanical Engineering students and one Industrial Engineering student was tasked with designing a device that has the capabilities to pick up a flash drive and replace it with a dummy flash drive. To accomplish this they developed a servo motor operated mechanical arm which also acts as a blade guard. The arm is made of a carbon fiber and birch wood sandwich and uses rare earth magnets to pick up the flash drive and an electromagnet to carry and release the dummy flash drive. Mu metal is also used to shield the magnetometer from the magnetic field produced by the magnets.

Figure 2: *2010 SDSM&T Retriever Arm*

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 to cancel the resultant torque from the rotors. The vehicle operates in the ”plus” control configuration which designates a front, rear, right, and left motor. To pitch forward, the front motor will reduce its RPM lower than that of the rear motor. In order to pitch back, the opposite operation is performed. Similarly for roll, the left and right motor will change their RPM with respect to one another to coincide with a change in attitude along the x-axis. The propulsion system on the MikroKopter platform is composed of custom electronic speed controllers (ESC) developed by MikroKopter, Robbe Roxxy 2824-34 brushless motors, and EEP1040 props.

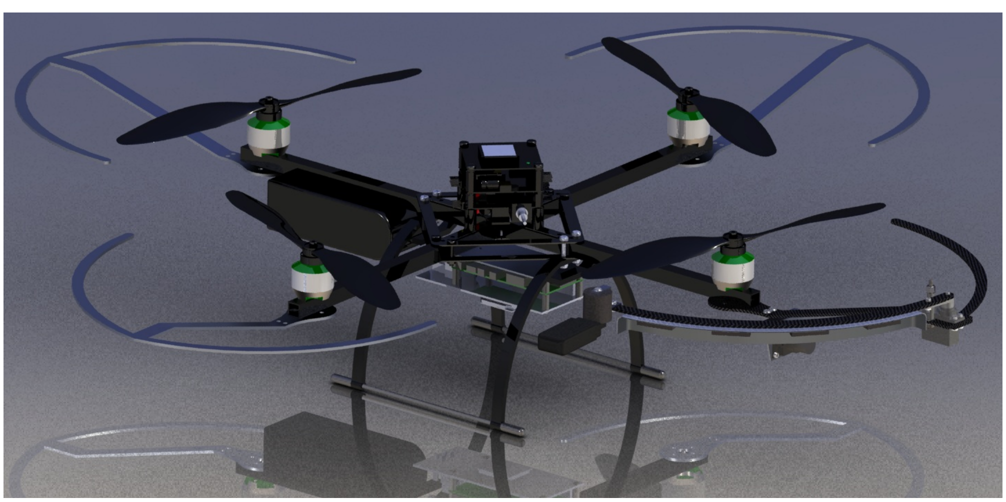

Figure 3: *2010 SDSM&T's Customized MikroKopter a.k.a. SERV*

2.2 Guidance, Navigation, and Control

Autonomous navigation and control is achieved via an autopilot system consisting of integrated COTS hardware, custom navigation solutions, and obstacle avoidance control algorithms. This system allows the flight path to be autonomously altered in real time in response to inputs from onboard sensors. Sensors include inertial measurement sensors and a Point Grey FireFly MV CMOS camera.

The MikroKopter M3-ME has a custom AHRS control algorithm on board the vehicle. The camera on the SERV is connected to the Gumstix Summit break out board for the Overo Fire. Once the video is compressed by the Overo Fire, it is transmitted over wireless 802.11g to the OCU where it is decompressed and fed into the image processing and the feature detection algorithms. The video image then moves into GraphSLAM, which generates the vehicle's current position and updates the 3D point cloud based on the latest features found in the video images. The obstacles defined by the feature detection algorithm and the 3D point cloud from the GraphSLAM algorithm will then be implemented into the path planning algorithm. The path planning algorithm will then generate a top down map, points of interest within the map, and coordinates of the points of interest. The MK Navi Controller will receive the waypoints of the points of interest from the OCU and translate the quadrotor to these waypoints. This method is used to take advantage of the robust AHRS on the MikroKopter. The monocular GraphSLAM algorithm will be used as feedback to help with error correction in the MK Navi Controller position loop. The vehicle will then be able to obtain accurate positioning and efficiently travel trajectories created by the path planning algorithm.

2.2.1 Stability Augmentation System

The attitude stability of the UAV is maintained by the flight controller on the MikroKopter. The flight controller's function relies on a 3-axis gyroscope, accelerometer, and magnetometer as well as a pressure sensor. The controller operates a PD attitude control algorithm. The GraphSLAM and path planning algorithms are primarily used to map the environment of the vehicle and provide error feedback for position control.

2.2.2 Navigation

Navigation of the vehicle and mapping of the environment is accomplished via the use of the GraphSLAM algorithm described by Eade. This algorithm estimates 3D locations of observed features in the environment as well as the 6D state of the observer, which in this case is the quadrotor. Modifications to the algorithm have been made to incorporate input from inertial sensors to improve state estimation.

2.2.3 Control System Architecture

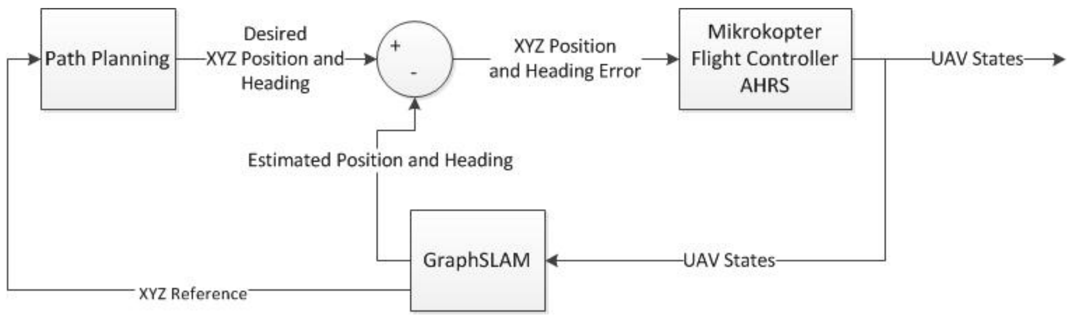

Figure 4: *SDSM&T Developed Control Block Diagram*

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 (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, video is compressed onboard by the Gumstix Overo Fire and then transmitted to the OCU for further processing. The processor on the MikroKopter Flight Controller is an Atmel ATmega644p which contains the AHRS. The Arm 9 processor on the MK Navi Control Board receives flight commands from the OCU.

3.1.1 GNC Sensors

The vehicle's primary sensor package consists of an Analog Devices 3-axis MEMS gyroscope, STMicroelectronics LIS344ALH accelerometer, and a Philips KMZ51 magnetometer in each of the three principal axes of the vehicle. A Freescale MPX4115A manifold absolute pressure sensor is used for altitude estimation and a Point Grey Firefly MV global shutter CMOS USB camera module provides image data for use by the GraphSLAM algorithm, feature detection, and display on the OCU.

3.1.2 Mission Sensors

The Point Grey Firefly MV camera is used to identify and locate the opening to the building, the blue LED which represents the security camera, laser barrier, obstacles, signs, and the flash drive. 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

All targets of interest in the current mission can be identified visually. As such, the target identification system relies on a video stream from the onboard camera. After the video stream is decoded on the OCU, it is passed to the Image Processing and Feature Detection Module. This module will, if necessary, examine the scene for any lit blue LEDs as well as detecting any scale invariant features in the image using the CenSurE algorithm [1]. The resulting features are then sent to both the GraphSLAM and Sign Detection Module.

The Sign Detection Module uses the scale invariant features detected by the Image Processing and Feature Detection Module and a series of sign templates to attempt to match the templates of features in the scene. Features associated with a detected object are then marked and the 3D location of the detected object can be determined by the location of features as described by the map generated by the GraphSLAM algorithm.

3.1.2.2 Threat Avoidance

Threat avoidance is accomplished through the path planning algorithm. Observed features are mapped using the GraphSLAM algorithm. These features correspond to physical objects in the environment and must be avoided. The path planning algorithm chooses a path that achieves the objective while maintaining a minimum distance from known features.

3.2 Communications

Communications between the Gumstix microprocessor board and the flight control boards will be done via the onboard UART serial communication ports built into the board. This will provide a near real time transfer rate and greatly reduce the chance for interference between the Gumstix and the MK Navi Controller. Communication between the Gumstix and the OCU will be carried out via WiFi on a IEEE 802.11g network. The Gumstix Overo Fire has a built-in 801.11g wireless module which provides a robust interface to any router used for communications with a maximum transmission speed of 54 Mbps. Communications regarding the vehicle status and navigation solutions will be sent via JAUS protocol according to the JAUS Standard Set. The flight termination system uses a separate XbeePro 2.4GHz module which sends an interrupt command to the onboard flight termination circuitry.

3.3 Power Management System

The SERV will use one 4200mAh Lithium Polymer 3 Cell 11.1v battery to fulfill the vehicle's power requirements. The SERV will draw an average of 25 amperes continuously. Planning for a current draw above average from the 4200mAh battery gives the SERV a 10 minute battery life. To ensure efficiency, each of the vehicle's components were carefully selected to optimize the vehicle's power consumption.

4 OPERATIONS

4.1 Flight Preparations

Before each flight, it is important that several tasks are completed to ensure a safe and successful flight. Each team member has been trained and assigned different duties which must be performed for each flight. Flight preparation includes members meeting to discuss the purpose and plan for the upcoming flight. This ensures each individual knows what tasks need to be completed and how they will be done. Safety checks are also performed (which are covered in section 5.2). It is critical that all team members are briefed about the flight to ensure a safe and successful flight.

4.2 Checklist(s)

Completing a preflight checklist determines if the SERV is in optimal condition to fly. The following list outlines the procedures completed before each flight.

1. Assign flight duties to team members.
2. Test vehicle and Radio batteries.
3. Inspect the SERV to ensure components are secure and functional.
4. Verify the direction of props and inspect the condition of the props.
5. Test communication between the SERV and the OCU.
6. Once all members are positioned and ready, the flight can begin.

Once the flight has begun it is necessary that throughout the entire flight, the vehicle is observed for mechanical failures and glitches. After a safe flight has been completed and all individual duties have been successfully accomplished, a post flight check list must also be performed. This checklist helps keep the SERV in flying condition after each flight has taken place.

1. Discharge and recharge batteries.
2. Inspect vehicle for loose hardware.
3. Inspect vehicle for mechanical and component failures.
4. Make repairs to vehicle (if necessary).
5. Store the SERV in a safe environment.

Each of these steps must be taken to guarantee the SERV is kept in optimal flying condition. Skipping steps could cause the vehicle to fail during a flight. Ignoring the checklists is a safety hazard that could lead to injury or vehicle damage.

4.3 Man/Machine Interface

The SERV has the ability to be flown manually and autonomously. To fly the SERV manually, a standard R/C transmitter is used to control the vehicle. The vehicle may also be controlled from commands given to the SERV from the OCU. The OCU interface allows for constant monitoring of mission critical functions and the ability to control the vehicle. When the SERV is flying autonomously it is completely controlled by processes on the vehicle and from processes delegated by the OCU. This will allow the SERV to make decisions faster by using the processing power of the OCU. When the vehicle is in fully autonomous mode it will be working to accomplish the mission, which has been defined previously in section 1.1.

5 RISK REDUCTION

5.1 Vehicle Status

Flight data for the SERV will be viewed via the OCU. Important flight information will be transmitted from the SERV to the OCU for immediate observation while also logging sensor data and vehicle states to allow for later flight comparisons, debugging, and tuning. This information will include vehicle altitude, vehicle attitude, video relay, battery status, and GraphSLAM mapping solutions.

5.2 Shock/Vibration Isolation

Shock loadings and high frequency vibrations are a major concern for flight operations of any VTOL aircraft. The most common scenario for shock loading arises during a hard landing. The landing gear has to be designed in a manner in which the energy can be dissipated before affecting operation of the system or damaging hardware. Since the vehicle used for this competition was commercially purchased, the landing gear design was assumed to have been designed to sustain this type of shock within reasonable limits of a standard flight.

High frequency vibrations are also very common in rotary wing vehicles. These 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 these high frequency vibrations are not experienced by the electronic hardware. The accommodations used to prevent these issues were rubber dampers placed between hardware mounts. For the current operation of the vehicle, it is assumed that the vibrations created by the rotors are damped sufficiently by the mounting hardware.

5.3 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.

The retriever arm was an area of concern because it contains both rare earth magnets and an electromagnet. The magnetometers on the SERV rely on the earths magnetic field to estimate the heading of the vehicle. Because this estimation is highly effected by any magnetic field, it was deemed necessary to test the effect of rare earth magnets and the electromagnet on the magnetometers. Preliminary testing revealed the effect of the magnets would be minimal with the proper amount of shielding. After the arm was implemented onto the vehicle, further testing was conducted which revealed a plus or minus six degree offset in vehicle heading. Mu metal was used as shielding and also structural support for the retriever arm. The testing showed that the effects of the rare earth magnets and the electromagnet are negligible with the mu metal.

5.4 Safety

Safety is one of the most important aspects of the SERV. When dealing with a flying vehicle, safety procedures are important to implement in order to ensure the safety of everyone present when flying. The MikroKopter airframe has been modified to prevent the propellers from hitting objects by enshrouding them with guards. There have also been precautions taken by instructing group members on proper actions to be taken while a flight is in progress. The first step is to hold a safety briefing before the flight to inform everyone of what needs to be done and where everyone should be during the flight. This is also the time when safety checklists as defined in section 4.1.1 should be started.

One of the most important responsibilities on the team is the kill-switch operator. This individual is trained to know when to flip the switch to terminate the SERV's motors. This is a safety precaution set up to prevent the vehicle from losing control and harming someone or causing damage during a flight failure. The kill-switch operator is trained to kill the SERV at the first sign of the vehicle losing control.

The team also has a strict training process for team members to become a certified pilot of the SERV. In order to become a pilot, the individual must log a minimum of forty hours on simulators and training vehicles. Once an individual has progressed through the training, they can be evaluated by a certified pilot to become a fully certified pilot themselves.

All data from flights and vehicle maintenance are recorded in a flight logbook to allow for proper management of the vehicles. When a vehicle has a problem the flight and maintenance log books can be consulted to understand problems during flight and maintenance that has been performed. To make sure no damaged parts are mistakenly used on a vehicle the team uses a red tag system to mark all damaged and dysfunctional parts. Team members are also trained on the proper methods to charge and discharge batteries to prevent damage or fires from improper use.

5.5 Modeling and Simulation

Modeling and simulation has played an integral role in development of both software and hardware in the recent past. There has been a strong push to create Solidworks CAD models of all the inventory such that physical alterations of any component can be designed within a digital world with ease. Noteworthy CAD models are certain MikroKopter airframes and an in-house quadrotor vehicle that is currently in development. Also, a true-to-life CAD model of a rotor was created with the use of a Faro Arm laser scanner.

Research on system behaviors has also been done with the use of numerical modeling. These models are important in the development of robust control systems on SDSM&T aerial vehicles. One area of emphasis to physical modeling is in the fluid dynamics of the rotor. Computational fluid dynamics (CFD) packages have been used to model simple rotor operating conditions. The computational modeling research has been based on the work done by Vicente Martinez at Cranfield University [3]. An effort has also been put forth to complete system identification on a motor/prop system. To accomplish this, a two motor one degree of freedom (DOF) test stand was operated with the use of Matlab's Instrument Control Toolbox.

5.6 Testing

Testing has been in progress throughout the year on multiple systems. The SDSM&T UAV Team has built a laser barrier with a mock camera which turns an LED on and off every 30 seconds. This device is located above the opening of the mock arena that the team constructed in May 2009. The retriever arm has also been tested. The team has successfully demonstrated picking up the flash drive and releasing the dummy flash drive under manual control. Vehicle testing has also been the cornerstone of research conducted on the team. In order to facilitate better understanding of the vehicles, all team members are encouraged to pilot the quadrotors.

The test stands mentioned in section 2.1 are all used for modeling verification and testing of control systems. The first test stand manufactured was a one DOF single motor-prop system arranged similar to a pendulum. The function of this test stand was to test the control of the system with the use of rotor dynamic modeling. The next test stand designed was a one DOF dual motor-prop system arranged similar to a "teeter-totter". The goal of this test stand was to mimic a quadrotor system as if it were fixed around a roll or pitch axis. The function of this test stand is to test the control of the rotational dynamics of the system. System identification of the motor-prop system is being researched on this platform to obtain a dynamic model of the motor-prop system. Although the data obtained from these testing apparatuses are not directly implemented into this year's vehicle, the knowledge obtained thus far has given the team a better understanding of the operation of the COTS vehicle and will eventually be implemented into future work.

(a) Rotor Pendulum Test System (b) Dual Rotor Test System

Figure 5: *SDSM&T Test Systems*

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 including security cameras and laser barriers in search of a flash drive, and transmitting live video to an operator control unit. Upon finding the target flash drive the UAV will extend an arm that will pick up the flash drive and release a dummy flash drive in its stead. Through this integrated design the SDSM&T UAV team intends to complete the sixth IARC mission in its entirety while demonstrating the possibility for other applications such as disaster relief, surveillance, and reconnaissance.

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