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

Randall Foudray, Jiayi Liu, Erik Kaitfors, Jordan Ritz

South Dakota School of Mines and Technology
Unmanned Aerial Vehicle Team
Rapid City, South Dakota

Abstract

The South Dakota School of Mines and Technology Unmanned Aerial Vehicle (SDSM&T UAV) Team will participate in the 2011 International Aerial Robotics Competition (IARC) with a single quadrotor helicopter. A stable commercial off-the-shelf (COTS) quadrotor is considered as the most appealing solution to complete the IARC. The purchased platform has been modified to autonomously locate and enter a one square meter opening, traverse a series of obstacles, and obtain and replace a USB flash drive. 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 fused algorithm with visual odometry and monocular visual Simultaneous Localization and Mapping (SLAM), along with the vehicle's attitude estimation and path planning, is implemented. The appeal of the current platform is that it is a low-cost COTS solution to completing the IARC.

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 while the blue LED above the opening is off. Stage 2 is defined as the ability to automatically traverse the corridors and rooms of the building in search of the chief of security's office which has a unique sign over the door. This is done while avoiding all obstacles and the laser barrier and continues on to detect a specific flash drive in that room. Once the flash drive is detect the vehicle will exit the arena. Completion of Stage 2 is a verification of a working visual based navigation system. Stage 3 is the process of identifying and picking up the target flash drive and dropping off a dummy flash drive. Stage 3 requires the integration of the vision system and the mechanical retrieval system. Completion of the mission occurs when the judges receive the target flash drive.

1.2 Conceptual Solution

The SDSM&T UAV team purchased a Parrot AR.Drone quadrotor to assist in the completion of the IARC. This vehicle will provide robust attitude control and position control along with the framework to expand the hardware, software, and sensor suite to complete the requirements of the IARC. The choice of platform is a result of extensive analysis of platforms used by the team in past IARCs and through research projects. Although there was an emphasis on using the stock AR.Drone airframe without alterations, small modifications were made to allow the AR.Drone to function as a research vehicle. Upgrades to AR.Drone's existing power systems and flight control concepts with the addition of visual odometry [4] and a path planning algorithm have progressed the AR.Drone into a robust operation vehicle.

The AR.Drone 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 AR.Drone will loiter in order to detect the blue LED. An on-board camera is used to send video data to the Operator Control Unit (OCU). A feature detection algorithm is then ran on the OCU which 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. When 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 visual odometry and object recognition algorithm on the OCU. The visual odometry module uses the downward facing camera on AR.Drone to capture sequential image frames, on which the optical flow field will be estimated. The localization algorithm 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 AR.Drone's custom ARM processor.

After ingress of the building has begun, the AR.Drone will then search for the flash drive. Once the flash drive is identified using feature detection, the AR.Drone will hover next to the inbox. While in hover it will sweep a magnetic strip located on a fixed carbon fiber boom to pick up the flash drive. The carbon fiber tube is necessary to remove the jump drive from the rotor wash. The AR.Drone processor will then send a current to a filament wire that will evaporate 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

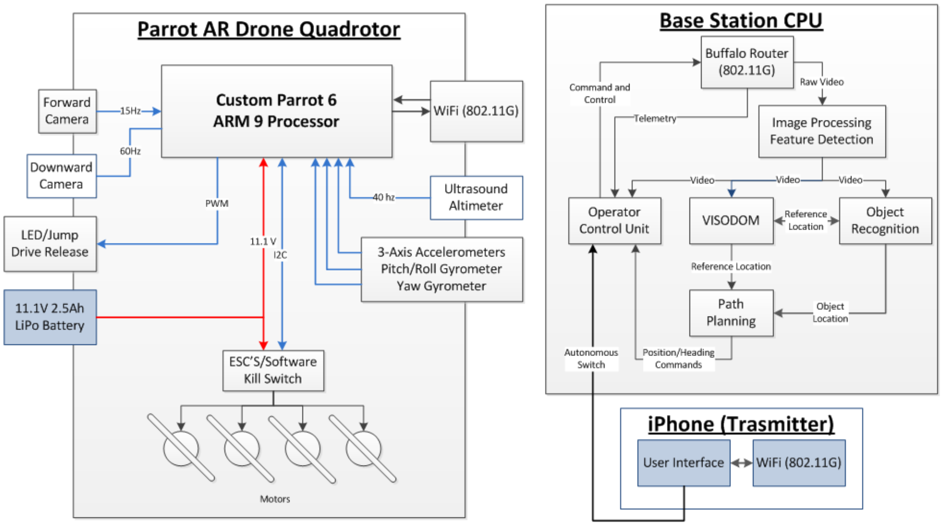


Figure 1: *2011 SDSM&T System Architecture*

1.3 Yearly Milestones

Following the previous year's competition milestones [5], the team has taken a different path in the development of the AR.Drone. Recently SDSM&T has aimed to focus more on intelligence rather than airframe development, but research and testing in commercial quadrotor vehicles has still been present. The COTS vehicles that have been extensively tested are from MikroKopter, Ascending Technologies, and Parrot. The team decided to pursue the Parrot AR.Drone due to its robust and stable attitude and position control without the need for physical modification. The interface with the vehicle has also been developed fully which has been a time limiting factor to the team in the past.

The main developments will come in the form of monocular visual odometry, path planning, and obstacle avoidance. The downward facing camera will be used to capture the ground Features from Accelerated Segment Test (FAST) [3] features as inputs to the visual odometry algorithm. Also the data from the built-in IMUs will be integrated to improve the visual odometry result. 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 visual odometry and develop a map, points of interest, and coordinates for the vehicle to follow. The coordinates are then converted into headings and sent to the AR.Drone.

2 AIR VEHICLE

2.1 Propulsion and Lift System

The AR.Drone is a COTS 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 propellers. The vehicle operates in the "x" control configuration indicating that there are sets of two motors used to translate the vehicle. For instance, to pitch forward the front two motors will reduce their RPM relative to the rear motors. In order to pitch back, the opposite operation is performed. Similarly, for roll, the left and right motors will change their RPM with respect to one another to produce a change in angle around the roll axis. The propulsion system on the AR.Drone platform is composed of electronic speed controllers (ESC), custom eight inch propellers, and 15W 35,000 rpm brushless motors that are geared to the propellers through a 1000:117 gear reduction ratio. All components are developed by Parrot.


(a) (b)

Figure 2: *2011 SDSM&T's AR.Drone*

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 on-board sensors. Sensors include a 3-axis gyroscope, a downward facing CMOS camera, a forward facing CMOS camera, and an ultrasonic altimeter.

The cameras are processed on the AR.Drone's custom ARM chip and sent over a 802.11g transmission to the OCU. The images are then fed into the image processing, feature detection, and visual odometry algorithms. The combination of visual odometry and feature detection will be processed by the path planning algorithm to find safe paths. The path planning algorithm will then generate a list of points and a list of interesting features near those points. The path will be converted to control inputs and these inputs will be sent back to the AR.Drone via the same 802.11g connection. 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 AR.Drone. The flight controller function relies on a 3-axis gyroscope, a 3-axis accelerometer, a downward facing camera, and an ultrasonic altimeter. The AR.Drone has built in control algorithms with feedback from the previously mentioned sensors. The altitude, attitude, yaw, and position are controlled internally by the on-board AR.Drone proprietary hardware and software. A path planning algorithm was developed by SDSM&T and is coupled with a tuned proportional-integral-derivative (PID) navigational control algorithm in order to reach commanded positions efficiently. The visual odometry and path planning algorithms are primarily used to localize in the arena environment and provide error feedback for position control.

2.2.2 Navigation

Navigation of the vehicle and mapping of the environment are accomplished via the fusing of the visual odometry and the monocular visual SLAM [6]. This algorithm estimates 3D locations of observed features in the environment as well as the 6D state of the AR.Drone observer. Modifications to the algorithm have been made to incorporate input from on-board inertial sensors to improve state estimation. The grid map will not be built from the algorithm; instead, a topological map describing the environment will be generated, which is a graph of nodes of way points with landmark information. In addition to maintaining a sparse map of landmarks by the SLAM module of the algorithm, the visual odometry module finds as many point matches between sequential image frames as possible. These point matches can provide additional constraints on the vehicle motion between frames, which leads to a more accurate pose estimate [6]. Also the location and the features of the way points will be used by the path planning algorithm described in Section 3.1.2.2.

2.2.3 Control System Architecture

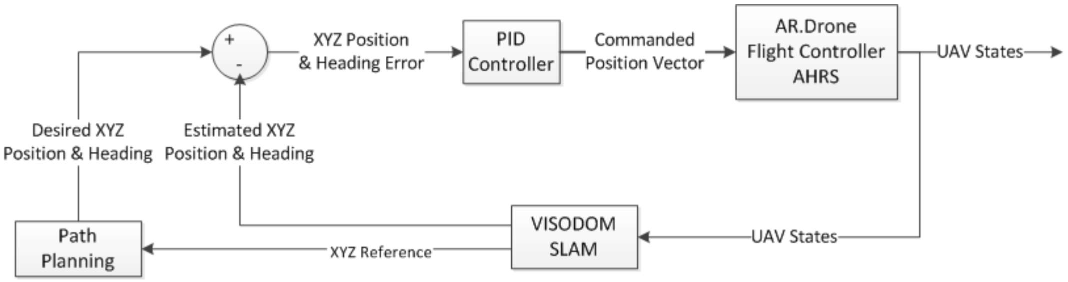


Figure 3: *SDSM&T Developed Control Block Diagram*

2.3 Flight Termination System

The flight termination system for the AR.Drone is a software implemented power cutoff to the rotors. In attention to safety, a wireless manual switch separate from the base station was developed. This is necessary so the base station operator can focus purely on the flight panel and not worry about when to kill the power to the vehicle. The switch consists of an electronic switch connected to a 2.4GHz XBeePro radio module. The radio module communicates with the base station software to implement a kill command to the on-board AR.Drone microprocessor. If communication is lost, the AR.Drone is programmed to hold a hover. Also the AR.Drone has a built in fail-safe that kills the motors if the pitch/roll angles reach a certain threshold. Both the internal fail-safe and the manual software switch render the vehicle ballistic.

3 PAYLOAD

3.1 Sensor Suite

The AR.Drone carries several on-board sensors whose outputs constitute the inputs to the control system, thus allowing autonomous fight. To complete specific tasks required by the IARC, the AR.Drone has several sensors mounted, including two cameras, facing forward and downward, an ultrasound altimeter, and a inertial measurement unit consisting of a MEMS 3-axis accelerometer and a 3-axis gyroscope.

3.1.1 GNC Sensors

The vehicle's primary sensor package consists of the aforementioned 6 DOF MEMS-based inertial measurement unit that is used primarily for attitude stability. An ultrasonic altimeter is used for altitude estimation. A downward facing CMOS camera provides image data for use by the visual odometry and base station display. A horizontal CMOS camera is used for feature detection and display on the base station.

3.1.2 Mission Sensors

The horizontal CMOS camera is used to identify and locate the opening to the building, the blue LED which represents the security camera, the 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 base station 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 on-board forward facing camera. After the video stream is decoded on the base station, it is passed to the Image Processing and Feature Detection Module. This module will, if necessary, examine the scene for any Speeded Up Robust Feature (SURF) [1] features. Using SURF features, objects can be recognized by unique collections of features. Object identification is done via feeding the features into an Artificial Neural Network (ANN) [2]. The ANN will be trained to recognize the desired targets, such as the entrance window, the lit blue LED, the signs, and the flash drive.

3.1.2.2 Threat Avoidance

Threat avoidance is accomplished by the path planning algorithm. Observed features are mapped using a series of descriptors embedded in a map of way points. 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 safe distance from known features.

3.2 Communications

Communication between the AR.Drone and the base station CPU will be carried out via WiFi on a IEEE 802.11g network. The AR.Drone 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 will be sent through TCP/IP ports controlled by Robot Operating System (ROS) nodes using the AR.Drone SDK. The flight termination system uses a separate XbeePro 2.4GHz radio module. The XbeePro sends an interrupt command to the software on the base station CPU which then transmits a kill command to the AR.Drone.

3.3 Power Management System

The AR.Drone will use one 2000mAh Lithium Polymer 3 Cell 11.1v battery to fulfill the vehicle's power requirements. It continuously draws an average of 5.5 amperes during a basic hover with spikes up to 7.5 amperes during translation. Planning for a current draw above average from the 2000mAh battery gives the AR.Drone approximately 15 minutes of battery life. To ensure efficiency, each of the COTS vehicle's additional components were carefully selected to optimize the vehicle's power consumption.

4 OPERATIONS

4.1 Flight Preparations

Before each flight, several tasks are completed by those attending the flight operation to ensure a safe and successful flight. Each team member has been trained and assigned different duties that 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 realized. Safety checks are also performed (which are covered in Section 5.4). It is critical that all team members and spectators are briefed about the flight to ensure a safe and successful flight.

4.2 Checklist(s)

Completing a preflight checklist determines if the AR.Drone 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 AR.Drone 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 AR.Drone and the OCU.

Once all members are positioned and ready, the flight can begin. When the flight has begun, it is necessary that throughout the entire flight, the vehicle is observed for mechanical failures and software 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 AR.Drone 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 AR.Drone in a safe environment.

Each of these steps must be taken to guarantee the AR.Drone 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 AR.Drone has the ability to be flown manually and autonomously. To fly the AR.Drone manually, a transmitter is used to control the vehicle. The transmitter may be a variety of devices that have software from Parrot installed. The transmitter of choice for the SDSM&T UAV Team is a base station CPU with customized software to communicate over IEEE 802.11g wireless. The base station interface allows for constant monitoring of mission critical functions and the ability to control the vehicle. When the AR.Drone is flying autonomously, it is controlled completely by a combination of processes on the vehicle and processes delegated by the base station. This will allow the AR.Drone to make decisions faster by using the processing power of the base station. 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 AR.Drone will be viewed via the base station. Important flight information will be transmitted from the AR.Drone to the base station for immediate observation. The base station will log this information to allow for later analysis, comparison, and debugging. This information will include vehicle attitude, battery status, responsiveness, and sensor information. If communications are lost to the AR.Drone, it will enter into a state of hover due to a built-in fail safe. Once communications are reestablished full control will be given back to the base station.

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 capable of sustaining this type of shock within reasonable limits of a standard height.

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 5000 RPM, causing the majority of the forced vibrations into the system. Design considerations have been taken by the developer to ensure these high frequency vibrations are not experienced by the electronic hardware. Foam surrounding the airframe and between mounting points of the rigid sensor bay are assumed to absorb most of the vibrational energy. 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 on-board components. Although these issues have been largely resolved on previous platforms, efforts are ongoing to identify sources of EMI/RFI on new platforms and eliminate or attenuate any negative effects. Shielding techniques are utilized whenever possible by the team, but the need for the AR.Drone to be physically modified was not necessary. These problems have been assumed to be handled by the manufacturer. To verify this, the AR.Drone has been determined to be European Conformity (CE) certified. The team is largely aware of the effect of EMI/RFI and contains knowledge on how to eliminate its effect if it becomes apparent on the COTS vehicle.

5.4 Safety

Safety is the most important aspect of operation of the AR.Drone platform. When dealing with a flying vehicle, safety procedures are important in order to ensure the safety of everyone present. The AR.Drone airframe has been designed to prevent the propellers from hitting objects by enshrouding them with a foam guard. 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 4.2, should be followed.

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 AR.Drone'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 AR.Drone 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 AR.Drone. 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

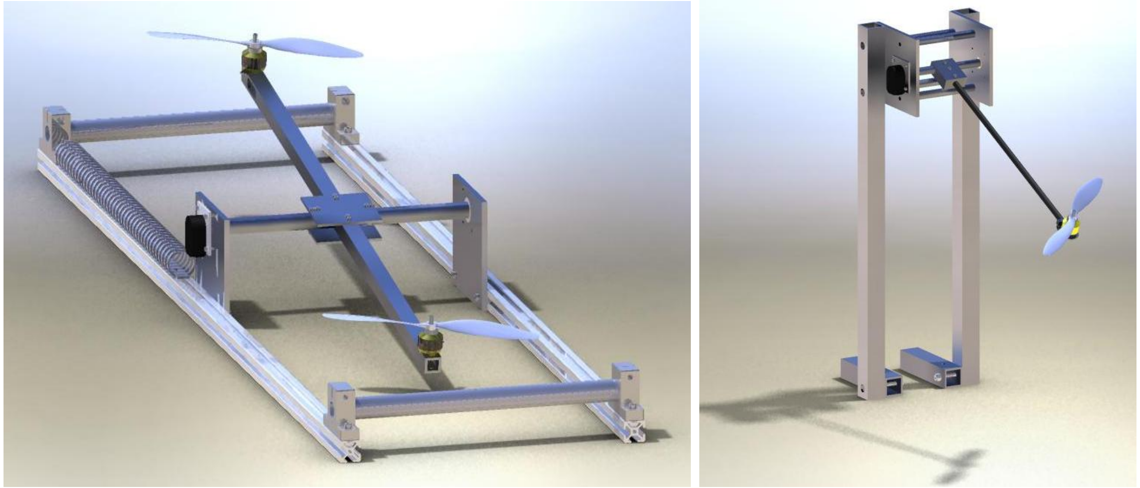
Modeling and simulation has played an integral role in development of both software and hardware. There has been a strong push to create 3D CAD solid models of all the team inventory so that physical alterations of any component can be easily designed within a digital world. Noteworthy SolidWorks CAD models are various MikroKopter airframes, the structure of the AR.Drone, an in-house quadrotor vehicle that is currently in development, and numerous test stands. Also, a true-to-life SolidWorks model of a rotor was created in the past with the use of a Faro Arm laser scanner. All models were made with the intention of use for manufacturing and with numerical modeling.

Research on system behaviors has been done with the use of numerical and analytical modeling. These models are important in the development of robust control systems on SDSM&T aerial vehicles. One area of emphasis in physical modeling is in the dynamics of the rotor system. Simple models of the fluid dynamics present in these systems were studied using 2d computational fluid dynamics (CFD). As this data was not completely useful for application, it served as a educational platform to teach team members about the basics of rotor dynamics. The most applicable model developed thus far has been gathered from system identification on a single rotor-motor system.

5.6 Testing

Testing has been in progress throughout the year on multiple systems. Last year, the SDSM&T UAV Team had 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 out of Tyvek and PVC piping in May 2009. Also, last year the team has successfully demonstrated picking up a flash drive and releasing the dummy flash drive under manual control with a servo driven arm mechanism. Through testing, it was determined that the weight of this mechanism hindered the performance of the vehicle. Because of this and the amount of modification needed to retrofit the mechanism to the current platform it has been deemed unfit for use on the current platform. In need of a new solution, the team tested a new light-weight design to retrieve and replace the jump drive. This solution will be attached to the AR.Drone for this year's competition and is one of the very limited amount of physical modifications to this year's platform. The details of this design are discussed in Section 1.2. Vehicle testing has also been the corner-stone of research conducted by the team. In order to facilitate better understanding of the vehicles, all team members are encouraged to pilot the quadrotors.

The test stands briefly mentioned in the previous section are all used for modeling verification and testing of control systems. The rotor pendulum test stand manufactured was a one DOF single motor-prop system in an arrangement similar to a pendulum. The function of this test stand was to test the control of the system with a rotor dynamic model obtained from an automated system identification process. 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 and verify a single rotor-motor system control law. System identification of the motor-prop system has been 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 COTS vehicles and will eventually be implemented into future work.



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

Figure 4: *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 sweep the inbox to 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.

7 REFERENCES

[1] Herbert Bay, Tinne Tuytelaars, and Luc Van Gool. Surf: Speeded up robust features. In *In ECCV*, pages 404–417, 2006.

[2] R.O. Duda, P.E. Hart, and D.G. Stork. *Pattern classification*. Pattern Classification and Scene Analysis: Pattern Classification. Wiley, 2001.

[3] Edward Rosten and Tom Drummond. Machine learning for high-speed corner detection. In *In European Conference on Computer Vision*, pages 430–443, 2006.

[4] Hauke Strasdat, J. M. M. Montiel, and Andrew J. Davison. Scale drift-aware large scale monocular slam, Imperial College London, UK, 2010.

[5] SDSM&T UAV Team. Design and development of south dakota school of mines and technologys aerial robotic reconnaissance system, 2010.

[6] B. Williams and I. Reid. On combining visual slam and visual odometry. In *Proc. International Conference on Robotics and Automation*, 2010.