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 2008 International Aerial Robotics Competition (IARC) with a two vehicle system consisting of an Airstar International Mongoose helicopter and a custom quad-rotor helicopter. The vehicles have been modified to work together and complete stages 1-3 in the 15 minute time limit of stage 4. The team will use the mongoose helicopter to carry the Structure Entry and Reconnaissance Vehicle (SERV) and deploy it once the mongoose helicopter’s onboard systems have identified the target building and its openings. The SERV will then enter the building through one of the openings and begin its search.

1 INTRODUCTION

1.1 Problem Statement

The goal of competing in the International Aerial Robotics Competition (IARC) is to complete a multi-stage reconnaissance mission using an autonomous aerial robot. To provide teams with annual milestones, the mission is divided into stages with different requirements. Stage 1 requires an aerial robot to fly a three-kilometer GPS guided flight path. Stage 2 requires the UAV to find a group of structures at the end of the three-kilometer ingress. Amongst this group of structures, the robot must identify one specific target building marked with the IARC symbol, and then identify all the openings on this structure. Stage 3 requires an aerial robot to enter this target structure through an opening, search the interior for a specific target of interest and transmit pictures or video data to the launch point. Stage 4 of the competition requires the completion of the first 3 stages contiguously in less than fifteen minutes.
1.2 Conceptual Approach

The South Dakota School of Mines and Technology Unmanned Aerial Vehicle (SDSM&T UAV) team has devised a two-vehicle system which is capable of completing the four stages of the IARC. The team has previously considered different concepts, including a five-vehicle system. However, with advances in controller technologies and a better understanding of the capabilities of our system, the team has determined that a two-vehicle system would be the most elegant, simple, and effective approach.

The system uses a mongoose helicopter to fly the three-kilometer ingress in under five minutes. The helicopter will then search the structures for a target symbol and identify all the openings on the nearest structure. A Structure Entry and Reconnaissance Vehicle (SERV) is carried by the helicopter during the three-kilometer ingress. Once the target structure and a viable opening have been located, the SERV is activated and deployed from the belly of the helicopter. The SERV navigates to a GPS point in front of the opening identified by the helicopter. From there, it uses its own sensor suite to navigate into the structure. Inside, it will stream video data back to the launch location, revealing any objects of interest. The SERV will continue to search the structure until its source of power is depleted. Once the SERV is deployed, the helicopter will remain in the air to serve as a communications relay. It will simultaneously search for additional symbols that could be located on nearby structures. If another target structure is found by the main vehicle, GPS coordinates for the new target will be relayed to the SERV so that it may navigate to the second structure after finishing its search of the first. Figure 1 illustrates the overall system architecture.

1.3 Yearly Milestones

Following the progress and milestones achieved at the 2007 IARC, the team has made substantial progress in developing a system to be highly competitive at the 2008 IARC. Improvements and modifications have been made to the Airstar International helicopter so as to increase reliability and improve component integration.

The helicopter has been flown numerous times autonomously, performing various maneuvers showing reliability and stability of the control system. Stage 1 flights have been completed at a speed of 10 m/s. The team’s Stage 2 technologies have been undergoing evolution and have shown substantial improvement in reliability and speed. The helicopter airframe itself has undergone prototype modifications allowing the system to carry and deploy the SERV while in flight. This deployment capability has been successfully demonstrated multiple times, and progress is being made towards adapting the deployment system for autonomous behavior.

The SERV has undergone a metamorphosis over the last year with its X-4 quad-rotor design being adapted for greatest efficiency and integration onto the main vehicle. The SERV’s control system has demonstrated indoor navigation which is being fine-tuned. Simultaneously, GPS integration is in progress. The SERV airframe has shown a lift capacity that is more than
adequate to carry the necessary sensor suite, power supply, and communication system while maintaining thrust for maneuvering.

With design architectures being focused on efficiency and systems integration, the team is forging ahead to meet the requirements to complete all four stages of the 2008 IARC.

2 AIR VEHICLE

2.1 Propulsion and Lift System

The SDSM&T UAV Team is operating an Airstar International Mongoose airframe. The airframe is a modified radio controlled helicopter with primary flight systems consisting of the engine and drive train, main rotor and tail rotor assembly, control actuators, and structural components. The airframe is powered by a 26cc, single cylinder, Zenoah G260H engine producing approximately 1940W (2.2hp) at 12,000rpm. The engine speed is governed onboard to maintain constant rotor head speed. The engine drives a clutch through a belt drive reduction system which is coupled downstream to both the tail rotor belt drive and a main rotor gear reduction set. The total reduction from the engine to the main rotors is 8.75:1, providing an operating head speed of approximately 1250-1500rpm.

The weight of the unmodified Mongoose airframe is approximately 6.1kg (13.4lb) dry. The payload the airframe is capable of carrying is approximately 6.4kg (14lb). The fuel capacity is 475cc (16oz), allowing approximately 45 minutes of flight without payload, and approximately 30 minutes of flight carrying full payload. The battery powering all onboard electronic components will provide approximately 90 minutes of power-on time for the entire system.

Various improvements were made to the existing helicopter propulsion system including the addition of cylinder head temperature sensors to accurately monitor engine efficiency and to aid in tuning the fuel mixture depending on location and altitude. A Hobbs meter was installed to digitally monitor and log engine operation time for maintenance purposes. In addition, a Zimmermann side-mount silencer was installed to reduce engine noise and to re-route engine exhaust to the rear of the airframe away from the SERV. These improvements added approximately $300 to the existing $11,000 total airborne system cost. The onboard computer case was extensively redesigned in an effort to increase system modularity and reduce system weight. The case was fabricated from aluminum to reduce weight while maintaining durability. In the event of an impact, the case's rubber mounts were designed to absorb energy before failing in shear, thus increasing the survivability of the internal computer components. Design elements were also considered to allow heat dissipation and to maintain an electrically shielded environment for the computer components.

2.2 Guidance, Navigation, and Control

Autonomous navigation and control of the main helicopter is achieved via a combination of the Rotomotion Automatic Flight Control System hardware (AFCS) and SDSM&T’s Mission Control Software (MCS). These two systems, in combination, allow the flight crew to design and execute pre-programmed waypoint paths that may be autonomously altered in response to
inputs from onboard sensors. The AFCS and MCS systems also allow for full control of the vehicle to be resumed at any time by the ground control station operator or by the safety pilot.

The MCS software executes onboard the main helicopter's computer and manages the guidance and navigation control behavior of the UAV system. The AFCS performs the attitude and position control of the UAV; it maintains the stability of the helicopter in hover and translational flight. The AFCS computer can store a waypoint stack, allowing the helicopter to follow a pre-programmed course even if it exceeds line-of-sight. The UAV will perform an autonomous translational maneuver only when the AFCS executes a waypoint flight path or when it is sent an interrupt waypoint from the MCS.

### 2.2.1 Stability Augmentation System

The stability of the UAV system is maintained by the Rotomotion AFCS, which consists of an embedded computer running Linux, a WAAS-enabled GPS unit, three accelerometers, three gyroscopes, and a three-axis magnetometer. It utilizes PID controllers to maintain attitude and altitude in translational flight, hover, and fast forward flight modes. The GPS unit is primarily used to maintain course, speed, and fixed hovering positions.

### 2.2.2 Navigation

The AFCS navigates the helicopter through the 3km flight path to the town via a pre-programmed waypoint stack. Following completion of the 3km ingress, the MCS assumes control of the vehicle navigation by generating flight commands based on sensor inputs. The MCS consists of three integrated software packages: Image Processing Software (IPS), Command Generation Software (CGS), and Target Location Software (TLS). The IPS interfaces with the onboard camera and laser range finder. It identifies the target symbol and windows on the target building, and then communicates the symbol location to the CGS. The CGS formulates commands in a format the AFCS can process; it compiles the commands into a flight path that is to be executed by the AFCS. In this manner, the autonomous flight path of the helicopter is altered in real time with the input from the IPS.

The Target Location Software receives distance measurements from the laser range finder and state data from the AFCS. The data is processed through reference frame transformations to determine the LLH coordinate of the target symbol. This coordinate is then used by the CGS to formulate a flight path for the SERV. Deployment of the SERV is initiated by the CGS, and the SERV subsequently navigates via GPS to the target building. Following deployment, the MCS maintains stable hover of the helicopter. Figure 2 illustrates the control system architecture.
2.3 Flight Termination System

The flight termination systems for the helicopter and SERV both use independent power sources and communication hardware. The termination switch on the helicopter is powered by an 11.1V lithium-polymer battery and uses a 900MHz Maxstream modem to communicate to a matched base unit. When the switch is activated, a relay short-circuits the engine spark to ground, killing the engine. The termination switch on the SERV uses a separate rechargeable battery and a 2.4GHz XBee modem. Power to the motor drivers is cut when the termination signal is received from a remote unit.

3 PAYLOAD

3.1 Sensor Suite

The helicopter 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. In order to manage all of this data, it was deemed simpler to handle most of the data processing onboard the helicopter, thereby eliminating communication issues of bandwidth and quality from air vehicle to base station. A mini-ITX computer has been mounted to the helicopter to perform these tasks. This computer consists of an Intel Core 2 Duo, 2.00 GHz processor, and 2 GB of RAM. The PC currently operates using a Fedora Linux system with an 8 GB Compact Flash card. The onboard operating system allows most of the sensor data to be compressed and/or relayed directly to the base station.

3.1.1 Guidance, Navigation, and Control Sensors

The Rotomotion AFCS utilizes a WAAS-enabled GPS unit, three accelerometers, three gyroscopes, and a three-axis magnetometer to define the current state of the helicopter. An Opti-Logic RS400 laser range finder is used to determine distances to targets of interest, specifically the IARC symbol. A uEye 2220c USB machine-vision camera is used by the Image Processing Software to identify the IARC symbol and windows on the building of interest. The uEye camera is also utilized by the Command Generation Software to alter the GPS flight path once the symbol has been identified.

3.1.2 Mission Sensors

The mission sensors are used to identify and locate the IARC symbol and building openings through which the SERV will enter. In addition, the mission sensors aid in guidance, navigation, and control as outlined in section 3.1.1. The Mission Control Software uses the mission sensors along with the guidance, navigation, and control sensors to complete all four stages of the International Aerial Robotics Competition.
3.1.3 Target Identification

Target recognition is achieved by first identifying scale invariant feature points within the image. After the points have been localized within the image, the gradients of a surrounding neighborhood of each point are sampled and rotated according to the overall gradient direction of the feature point. The values of the gradient are used as a feature point descriptor and are then fed into a neural network. The neural network classifies them as matching one of the template features or an environmental feature point. All of the template matching features are then used as the input for the Random Sample Consensus (RANSAC) algorithm to determine whether or not the features uniquely identify a match with the template or are a collection of false positives. A significant return from the RANSAC algorithm is considered a match.

After the symbol has been identified, the image processing software must then begin identifying all the windows and entrances. The method selected for this portion of the software is a two-part algorithm. Used at the 2007 IARC competition, a Canny edge detector followed by a connected components analysis identified windows and doors very well. Unfortunately, it had a reasonably high false positive rate. The team has opted to utilize the same algorithm for the 2008 IARC, but to augment it with watershed segmentation to help eliminate the false positives.

Once the target has been identified, its LLH coordinate must be determined by the Target Location Software (TLS). The TLS rotates and translates the laser range finder distance vector from the camera platform reference frame to the body reference frame. The vector is then transformed into the tangent plane and thereafter into the ECEF Rectangular (x,y,z) frame. The final LLH coordinate of the target symbol is obtained through an iterative calculation which converts the ECEF (x,y,z) coordinate to an ECEF Geodetic (LLH) coordinate. Finally, the LLH coordinate of the target window is calculated relative to the LLH coordinate of the symbol.

3.1.4 Threat Avoidance

The helicopter uses its onboard navigation and guidance systems to determine its altitude above ground level (AGL). Using this information, the helicopter will fly at a high enough altitude such that it will be able to avoid trees and structures.

3.2 Communications

After substantial research and experimentation, the team decided to move all its communications to an IEEE 802.11g wireless network. The onboard computer and AFCS are connected to a Buffalo Air-Station Wireless G router, which creates a wireless link between the UAV and the base station. The router is enclosed within an electrically isolated, single-point grounded aluminum case to minimize RF/EMI interference. The base station computer can use its inbuilt wireless card to connect to this network for short-range applications. However, to extend the range of communications, the base station is connected to a similar Buffalo wireless router. This system has been shown to be reliable at a range of approximately 3.2km with the helicopter hovering.

One of the team’s primary motivations to move to the IEEE 802.11g system was the ability to integrate the SERV’s communications into a single decentralized system where the SERV and
helicopter communicate with each other as well as with the base station. This system has proven to be the most reliable communication system the team has used thus far.

3.3 Power Management System

The team has altered its approach to the power system in order to incorporate simplicity and dependability while maintaining performance capabilities. The result is a power system consisting of a Thunderpower 3S2P, 4200mAh, 11.1V Lithium-Polymer battery, which is used to directly power the onboard PC power supply and the AFCS. This crucial component has proven its reliability through extensive testing and has therefore remained as the helicopter's main source of power. The 2.4GHz Buffalo Router and the servo control board are powered by 5V rails on the PC power supply. The SERV uses its own dedicated 11.1-volt Lithium-Polymer battery, supplying power directly to the motors and onboard systems.

3.4 Sub-Vehicle

Following design and development of previous years, the team has chosen a sub-vehicle utilizing an X-4 quad-rotor configuration. This platform consists of four fixed, upward thrusting fan assemblies configured in two counter-rotating pairs. These fan assemblies are mounted onto a single chassis as shown in Figure 3.

The team has investigated various vehicle platforms, which included a compact chassis made from four commercially available ducted-fan assemblies. Following tests which did not yield anticipated results, the team investigated a platform based on the commercially available X-UFO chassis. However, this platform also did not yield the expected or necessary performance.

Going back to an already capable and proven platform, the team has chosen the Draganflyer flying model chassis and motors for the platform development. This platform flies with a leading and trailing rotor, both turning in the same direction, and two side rotors turning in the same direction, but opposite to the first pair. Flight maneuvering such as pitch, roll, and yaw are accomplished by complimentary adjustment of rotor pairs.

The vehicle is equipped with a MEMSense Nano IMU which is a temperature corrected inertial measurement unit consisting of 3-axis accelerometers, 3-axis gyroscopes, and a magnetometer. The angle of the vehicle with respect to the gravity vector as well as the earth's magnetic field is extracted using a complementary filter. Work is also progressing on an Extended Kalman Filter. An accurate representation of the vehicle's attitude is created from the information gathered from the gyroscopes, combined with the information from the magnetometer and accelerometers. The attitude controller on the SERV uses the angular rotation and the angle of the vehicle to maintain a desired attitude.

A uBlox GPS unit is being used onboard to ascertain the vehicle's GPS location for outdoor flight. Using gumstix modules, the SERV processes the data necessary to maintain stable GPS flight. The gumstix module has a 900MHz processor onboard to handle the necessary computations. The gumstix modules are also capable of wireless IEEE 802.11g communications.

Figure 3: SERV Design
and will be integrated into the overall system communications architecture, allowing the SERV, the helicopter, and the base station to communicate with each other in the same network. Using the target identification method discussed in section 3.1.4, the helicopter will communicate the position of the opening on the target building to the SERV. The SERV will then be deployed and navigate to the opening using its GPS capabilities. As the SERV approaches the window, its vision system will perform edge detection to align itself directly in front of the opening.

The flight operations outlined above are governed by the guidance and navigation controller which has indoor and outdoor modes. Fuzzy logic is used to prevent conflict between the two modes. The SERV will navigate via GPS waypoints from the main vehicle to the target building. Since GPS data is unavailable indoors, a separate control scheme was developed for the transition to indoor flight. The indoor mode includes a velocity controller and an indoor rotation controller. The indoor sensors consist of ultrasonic sensors, which allow the SERV to determine its distance from walls and other objects. These sensors and the onboard camera will perform the search of the building. Figure 4 illustrates the SERV control system.

![SERV Control Diagram](image)

*Figure 4. SERV Control Diagram*
4 OPERATIONS

4.1 Flight Preparations

Prior to any flight, several tasks are to be performed to ensure a successful mission. Team members are assigned duties for which they have been trained. A safety briefing is held with everyone on the field before the system is turned on. The purpose of the briefing is to make known all the associated hazards and risks that are present. The briefing also covers a flight plan and defines vehicle behavior which may necessitate emergency procedures. The briefing ends 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 day.

4.2 Checklists

The team follows a set of checklists for its pre-flight, launch, in-flight, and post-flight procedures. The rotors, engine, avionics, flight controls, radios and other systems are all examined for safe operation. The team also formulates a general flight plan which outlines the maneuvers and overall expectations for each flight. The checklist and log entries must be completed before proceeding with the flight.

4.3 Man/Machine Interface

Currently under development is a single base station application capable of managing the entire two-vehicle system on a single, standard PC or laptop computer. Through the use of a GUI, the operator will be provided with maps, video, flight information and mission information. This software will also allow the base station operator to control the UAV in a semi-autonomous mode by clicking on USGS maps or by executing a waypoint script.

Both the main helicopter and the SERV can be operated separately, each through independent GUI interfaces. The main helicopter may be flown by an operator using the Rotomotion AFCS Ground Control Software. The operator is able to monitor all mission critical data through this interface while simultaneously operating the helicopter in autonomous mode. Similarly, the SERV may be operated manually or autonomously through SDSM&T's custom GUI interface which displays all data critical to SERV flight.

5 RISK REDUCTION

5.1 Vehicle Status

The status of the helicopter is monitored in several ways. Each flight is logged through Rotomotion software and the total flight time is recorded, allowing the team to keep regular maintenance schedules. Prior to each flight, mechanical and system checks are performed to verify the system is flight worthy. Several onboard sensors monitor the status of critical systems such as battery voltage, engine cylinder head temperature, and engine RPM.
5.1.1 Shock/Vibration Isolation

High frequency vibration can lead to fatigue and failure of various mechanical and electrical components. These vibrations can also lead to errors in the AFCS sensor outputs. Isolators have been implemented on the electronic component housings to avoid natural frequencies near the forced vibration frequencies from sources such as the engine and main rotor blades, approximately 100-200Hz and 20-25Hz respectively. In the event of a hard landing, the landing gear and electronic component housing mounts are designed to dissipate energy by deforming and protecting the vital system components from impact damage. Design considerations have also been taken to ensure that the integration of the SERV and landing gear do not lead to increased vibration amplitude.

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 EMI/RFI 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. System component power requirements have been standardized to eliminate interference sources from multiple power regulators. Noise-producing systems have been eliminated wherever possible, and any new components introduced are scrutinized for EMI/RFI. Individual components and un-amplified signal wires have been shielded and ground loops have been minimized to protect against EMI/RFI.

5.2 Safety

The team has established a safety plan which outlines the procedures to be followed if a situation is encountered that threatens the safety of the team and/or vehicles. All team members are given training on flight safety rules and are expected to follow these rules at all times. A briefing is held prior to any flight where specific safety hazards 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 termination switch and its implications are emphasized in training. There is a special training process for vehicle pilots. 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 a logbook, along with any routine maintenance performed on the vehicles. 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.
5.3 Modeling and Simulation

Modeling of the main helicopter has been completed using Solidworks. Mass and material properties were modeled in order to accurately calculate the center of gravity and moment of inertia characteristics of the system. In addition, the SERV has been designed and modeled in conjunction with an extensive redesign of the helicopter landing gear and SERV release mechanism. By modeling the two vehicles simultaneously, as illustrated in Figure 5, the designs were integrated while preserving the compact, vibration-resistant nature of the system.

Low-level control simulations, testing the stability of the IMU and PID controller onboard the SERV have been coded in Matlab. A high-level simulation application has also been developed called SimSERV. This application simulates the mission sensors onboard the SERV.

Pertaining to the overall high-level architecture of the mission, models of the Mckenna MOUT site have been created using Google SketchUp as seen in Figure 6. These models interface with Google Earth maps, allowing the team to visualize the site in 3D and with GPS reference coordinates. Flight paths and search algorithms may be established with accuracy only affected by GPS drift. This system has proven to be useful in establishing the logistics of mission planning without having direct access to the MOUT site.

5.4 Testing

Flight-testing immediately resumed following the 2007 IARC. Main helicopter autopilot tuning was conducted, resulting in a successful demonstration of 3km flight at 10m/s in August 2007. Testing of a prototype SERV deployment mechanism was conducted throughout September and October with a successful airborne SERV deployment in November, 2007. Bench testing of the Image Processing Software and Target Location Software began in January 2008, with flight testing of the software beginning in late April. Flight testing continues to take place with final system demonstrations scheduled in early June.

Bench and flight tests have also continued with the SERV to further develop the AHRS and progress toward GPS guided navigation. Extensive testing has been conducted to accurately calibrate the sensors used by the SERV AHRS. Development continues on the INS and sensor integration, with flight demonstrations scheduled in June.
6 CONCLUSION

All of the systems discussed above, when fully operational and integrated, will be capable of meeting the four stage requirements of the IARC competition. While ensuring success in the competition, the system will also be suitable for other applications such as disaster relief and surveillance. This makes the system and the team more adaptable to new competitions, missions, and research.

In order to complete stage 1 of the 2008 IARC competition, the Mongoose helicopter will fly the required three kilometers while carrying the sub-vehicle. After completing the three-kilometer ingress, the helicopter will reach the group of structures to be searched. Using search algorithms and image recognition software, the system will identify the symbol and openings on the target structure to complete stage 2. Following this, the sub-vehicle will be deployed from the helicopter, enter the target structure and begin to search for any objects of interest, thus completing stage 3. The system will complete the above-cited tasks in less than 15 minutes so as to satisfy stage 4 requirements.

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8 REFERENCES