Unmanned Vehicles, Sensors and Performance Testing for Near-Earth Missions

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Abstract

Disaster mitigation requires a diverse set of workers to respond quickly to dangerous situations. Robots performing tasks such as bomb detection, search-and-rescue and reconnaissance could be used to conserve resources and minimize risk to personnel. Such tasks require the cooperation of heterogeneous robotic teams. This paper surveys the design of aerial and ground based robots for disaster mitigation. An aerial robot platform and sensor suite design are presented. A robotic ATV with casualty extraction device is discussed, and a platform for investigating aerial and ground robot teaming is introduced.

1 Introduction

First responders reacting to disaster scenes must act quickly and decisively. In such time critical situations it is essential to gather information about the event and get emergency care to victims. When the environment is difficult or hazardous for humans to work in, robots can be employed to perform missions such as reconnaissance, damage assessment, or evacuating the injured.

Aerial robots provide an effective means for traversing rough terrain. Deployed remotely, they can navigate to areas of interest, loiter overhead and provide an aerial view of the disaster site. Their effectiveness for such missions has been proven in previous disaster scenarios [2] [7] [3]. This situational awareness can be used to identify casualties, plan inlet and egress routes, and identify points of interests such as collapsed buildings.

Ground robots can then be mobilized to search structures, deliver aid or extract victims. Since ground robots do not face the same payload constraints as aerial robots, they can be outfitted with equipment to fit the task. Their worth has been proven in search and rescue missions, bomb extraction and remote detonation [10].

By teaming aerial robots with ground based robots, emergency responders can be equipped with a network of robotic assets capable of effectively handling a diverse set of situations. While many successes have been made towards this goal [5], testing heterogeneous robot teams for robustness in the field remains difficult. Research at the Drexel Autonomous Systems Lab (DASL) seeks to identify and address the key challenges associated with developing these networks of robots.

This paper outlines several of the core research projects being conducted at DASL. Section 2 describes an aerial robot that can fly like a plane and hover like a helicopter. Section 3 covers the use of optic flow sensors for navigating aerial robots in cluttered terrain. A facility for testing aerial robot sensors and control algorithms is presented in Section 4. Section 5 outlines a ground based robot and casualty extraction device. Research into teams of aerial and ground robots is covered in Section 6. Finally, conclusions and future work are discussed in Section 7.

2 Blackhawk

Homeland security, search-and-rescue, and disaster mitigation efforts in cities, forests, tunnels, or even inside urban structures present hazardous and dynamic environments. Performing tasks such as surveillance, reconnaissance, bomb damage assessment, or evacuating the injured within such territory is dangerous and requires a large, diverse task force. However, unmanned robotic vehicles can assist in such missions by providing situational awareness without risking the lives of soldiers, first responders or other personnel.

Backpackable, bird-sized aircraft or Micro Air Vehicles (MAVs) can be rapidly deployed to provide an over-the-hill or around-the-corner perspective from a

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Figure 2: This figure shows video stills from blackhawk hovering under manual control (top) and autonomous control (bottom). The benefit of autonomous control can clearly be seen.

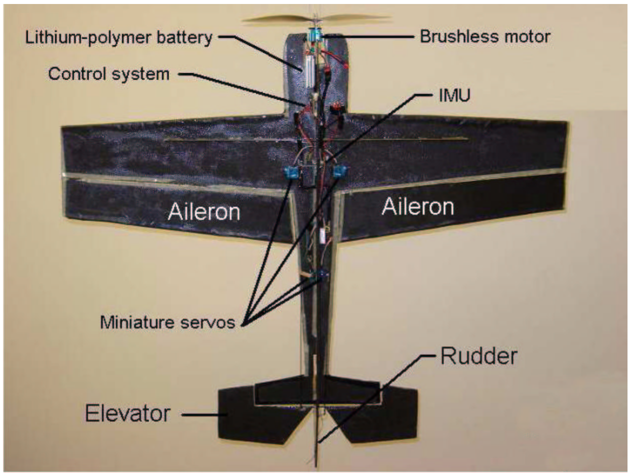

Figure 1: The MAV Blackhawk, designed to fly like a conventional airplane and hover like a helicopter. The brushless motor and large propeller allow it to perform prop hanging. An IMU provides inertial measurements which are used to stabilize the craft.

remote location. Fixed-wing MAVs have long flight times and therefore have large operating ranges. However, they must constantly remain in motion making them undesirable for hover-and-stare or perch-and-stare missions. Rotary wing craft are ideal for missions requiring hovering. This ability also enables flight in caves, tunnels, and other tight, enclosed labyrinths. However, they do not have the same endurance as fixed-wing craft.

We are currently designing Blackhawk, a MAV platform that offers both the endurance superiority of a fixed-wing aircraft coupled with the hovering capabilities of rotary wing vehicles. This is achieved through a flight maneuver known as prop-hanging. During a prop-hang, the longitudinal axis of the fuselage remains vertical while the weight of the aircraft is supported by the thrust from the propeller. This requires unconventionally large thrust-to-weight ratios. The net result is a vehicle which primarily translates but can perform high angle-of-attack (AOA) maneuvers as a secondary flight modality.

In order to transition into and sustain a hover, a thrust-to-weight ratio greater than 1 is required. With a weight estimate of 600 grams, a brushless motor was selected which can generate more than 1000 grams of thrust (i.e. a T/W = 1.67). Another design factor is that the aircraft must be controlled with limited airflow (i.e. prop wash) over the control surfaces once in the hovering position. As a result, the control surface areas of the vertical and horizontal tails and wing must also be increased, depicted in Figure 1.

To enter the hovering flight mode, the MAV must first transition through the critical high angle-of-attack regime. To achieve the maneuver, the aircraft has to leverage its momentum and essentially overpower its way through the stall regime. The aircrafts high thrust-to-weight ratio helps to preserve momentum through this transition, thus avoiding stall.

After a successful transition to the secondary flight mode, sustaining a hover under manual control is very challenging. The maneuver requires that an expert human pilot continuously manipulate four channels of a radio-controlled transmitter. The two most demanding tasks in manual hovering include keeping the aircrafts yaw and pitch orientation constant through rudder and elevator deflection, respectively. These axes must be controlled to enable autonomous flight.

In order to make the secondary flight mode autonomous, the aircrafts attitude needs to be measured and fed back to an on-board control system. Microstrains 3DM-GX1 inertial measurement unit (IMU) consists of three orthogonal accelerometers and gyros which are interpreted to output orientation at a rate of more than 100 Hz. The sensors small size (65 mm x 90 mm x 25 mm) and weight (30 grams out of protective casing) enable it to be easily mounted to the MAV platform. The IMU interfaces with a control circuit which includes a PIC16F87 microcontroller and a RS232 converter chip to communicate serially with the sensor.

During cruise flight, the control system acts as an autopilot by controlling the rudder, elevator and ailerons to maintain steady level flight. The throttle is controlled manually to allow for altitude adjustment. To demonstrate the effectiveness of the controller, a human pilot was initially given control of the aircraft and was instructed to fly around a gymnasium in cruise configuration. Then, after manually making the transition from cruise to hover flight, the pilot attempted to hover the aircraft for as long as possible. The video stills in Figure 2 show the pilot struggling to keep the fuselage vertical. The human pilot was able to sustain a hover for several minutes, but was unable to stabilize the aircraft in the vertical position.

Next, the pilot was instructed to again fly in cruise configuration and manually make the transition from cruise to hover flight. However, instead of trying to hover the aircraft manually, the pilot flicked a switch on the transmitter which enabled the on-board controller. This time, the aircraft is fixed in a vertical position and is able to hover for minutes before draining the battery.

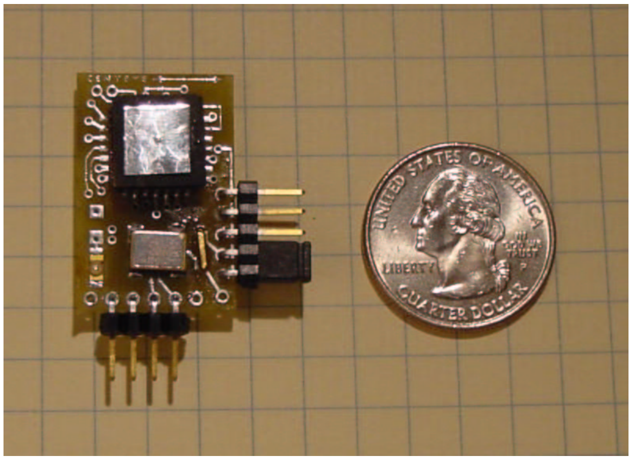

Figure 3: The Ladybug optic flow sensor. The sensor detects motion in the visual field in much the same way that bees and flys do.

Autonomous hovering allows the aircraft to operate in environments densely populated with obstacles. However, to autonomously navigate these environments, the robot must be equipped with obstacle avoidance sensors and control laws.

3 Optic Flow Based Navigation

Aerial robots that can fly in near-Earth environments such as urban canyons, forests and tunnels require sensors to help them negotiate the environment. Conventional navigational sensors, which work effectively for ground-based robots are too heavy and large for MAVs which typically can only carry up to a cubic inch of payload weighing a maximum of 0.5 pounds. Some sensors, like global positioning systems, though small and light, dont work indoors and in enclosed near-Earth environments like tunnels or caves. Small and light navigational sensor suites are required to fly in near-Earth environments.

Looking at [11], it is evident that flying insects like honeybees utilize optic flow to maneuver through regions with dense obstacle fields. Insects perform tasks like collision avoidance, altitude control, takeoff and landing and can therefore serve as a model for MAV flight patterns in such environments. The recent development of optic flow microsensors such as that picture in Figure 3 makes it possible to investigate insect-inspired navigational methods.

Optic flow is the measurement of apparent motion in the visual field. For example, while in flight, objects which are close have higher optic flow magni-

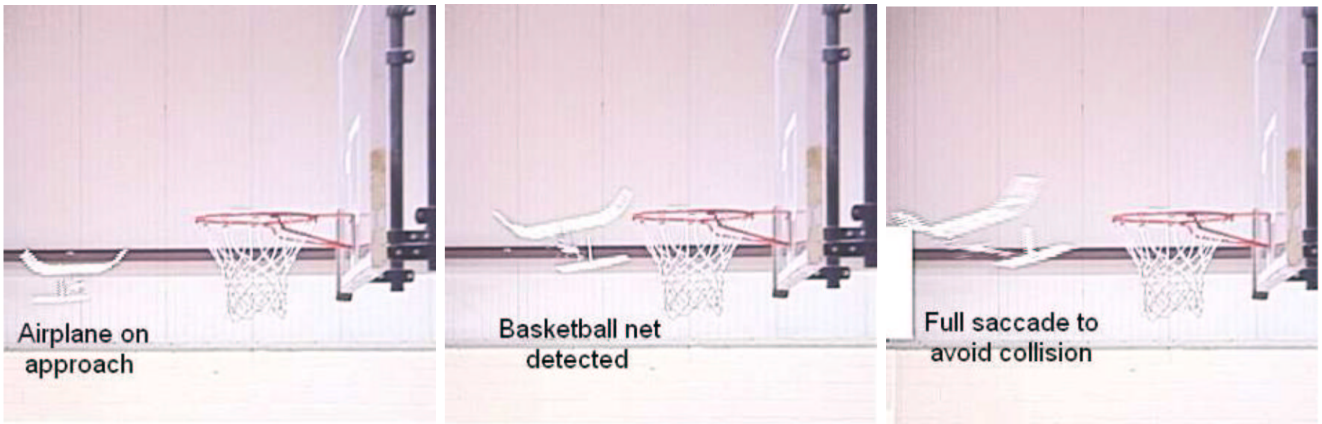

Figure 4: The plane with optic flow sensor was directed towards an obstacle. As the plane approaches, the optic flow value increases, and the plane saccades to avoid the obstacle.

tudes than objects in the distance. Thus, an MAV must saccade (or turn) away from regions of high optic flow to avoid collisions.

An optic flow sensor was mounted to an MAV operating indoors. Several different configurations were tested to exhibit different behaviors. With the optic flow sensor pointed towards the ground, the craft was able to perform autonomous take off, landing, and altitude control [6]. With the sensor pointed towards the front of the craft, obstacle avoidance was demonstrated as shown in Figure 4.

This technology performed well in controlled conditions. However, to ensure robust performance in the myriad different environments that the craft would encounter, a testing platform that could mimic real world conditions was required.

4 Systems Integrated Sensor Test Rig

Flying autonomously in near-Earth environments demands a sensor suite that can perform in cluttered areas where GPS often fails and communications are degraded. Additionally, the sensor suite must operate during day or night, despite adverse weather conditions and obscurrants, like fog, rain or dust. A key gap in the knowledge domain is the absence of metrics characterizing the performance of a sensor in near-Earth environments. Consequently, much of the integration of sensor and air vehicle has been ad hoc and happenstance. Metrics like resolution, dynamic range, bandwidth and signal-to-noise ratio are important parameters that are needed to compare one sensor to another.

To address this gap, the Systems Integrated Sensor Test Rig (SISTR) pictured in Figure 5 is being developed. SISTR will be able to repeatably and controllably capture performance metrics. The final rig will have a six degree-of-freedom end effector. Attached to the end effector is a non-flying mockup of the aerial robot that will be retrofitted with candidate collision avoidance sensors. The mockup emulates the motions of the real vehicle. Here, sensor data feeds into a high-fidelity math model of the real-world aircraft. The math model is then realized by SISTR using model reference adaptive control.

SISTR can be outfitted with testing apparatus to simulate real world conditions. Overhead lights and light blocking curtains provide a variety of lighting conditions, ranging from a moonless night to dawn. A rain machine was constructed to provide a “sheet” of rain which can be introduced in front of the sensor. Flow rates can be varied from a light drizzle to a downpour. A dust machine and fog system test for the effect of obscurrants on sensor performance.

The net effect is a hardware-in-the-loop system to capture metrics that expose aerial robot performance in places like forests and buildings. This is important because such metrics help fill the gap in the knowledge domain and provide an analytical framework to design near-Earth aerial robots and vertically advance the field.

In practice, DASL serves as an “honest broker” in sensor suite design, utilizing SISTR to provide ground truth information regarding sensor performance in real world conditions. This service was commissioned

Figure 5: Systems Integrated Sensor Test Rig (SISTR). Sensor suites attached to the end effector feed data to the controller, which actuates the end effector based on the math model of the craft. This allows control algorithms to be tested against real world sensor data.

in the design of a Class II UAV for Future Combat Systems. LIDAR, sonar, optic flow and UWB radar sensors were characterized under varying weather conditions as potential candidates for collision avoidance sensors. Figure 6 shows a SICK laser range finder being tested under foggy conditions. The SICK was found to be particularly sensitive to obscurrants.

SISTR has also been used to demonstrate basic collision avoidance algorithms [8]. An infra-red ranging sensor was mounted to the end effector. The end effector was instructed to move through an obstacle ridden path. Control laws implemented in SISTR successfully guided the end effector around the obstacles. Pending completion of the remaining 3 degrees-of-freedom, SISTR will be able to assess the performance of control algorithms using the math model of real aircraft.

5 Drexel's Integrated ATV System

After overhead reconnaissance has been accomplished, ground vehicles must be implemented to deliver

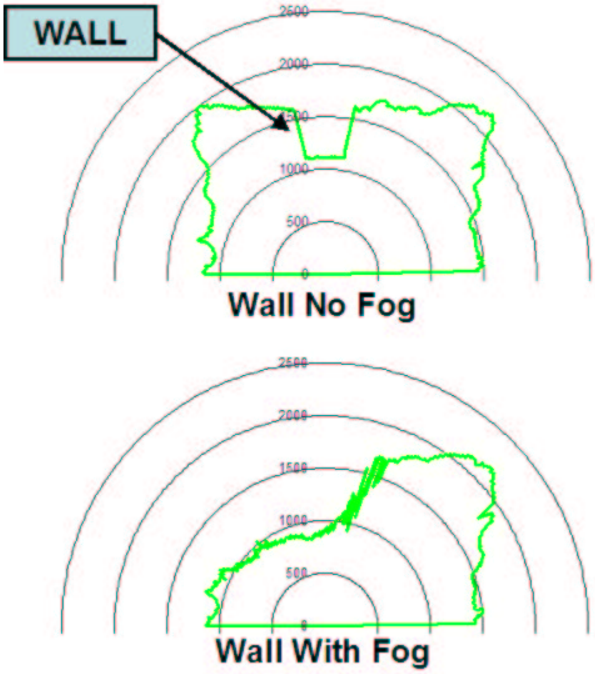

Figure 6: SICK laser range finder undergoing a fog test. With no fog present, the sensor clearly detects a wall 1 meter away. The presence of fog blinds the sensor, obscuring the wall.

resources and extract casualties. Typical robotic ground vehicles are built on top of stock all terrain vehicles (ATVs) [4]. This prevents a person from using the vehicle as if it were stock. Moreover, the systems are often heavily customized and can not be ported onto other vehicles. To address these issues, DASL has developed the Drexel Integrated ATV System (DIAS).

DIAS, pictured in Figure 7, is a dual-mode robotic retrofit for an ATV. In robotic mode DIAS is capable of being driven with a standard RC controller or navigated through GPS waypoints. At the flip of a switch, DIAS can be engaged in manual mode. This allows a person to drive the ATV as if it were stock. All of the 4 major axis of the ATV - steering, braking, throttle and shifting - are controlled through systems that act in parallel to the stock functionality.

The steering system utilizes a DC motor coupled to an electric clutch which rotates a chain drive mechanism that turns the steering shaft. In robotic mode, the clutch engages allowing the DC motor to turn the wheels. Steering position feedback is provided via an absolute potentiometer on the steering shaft. The

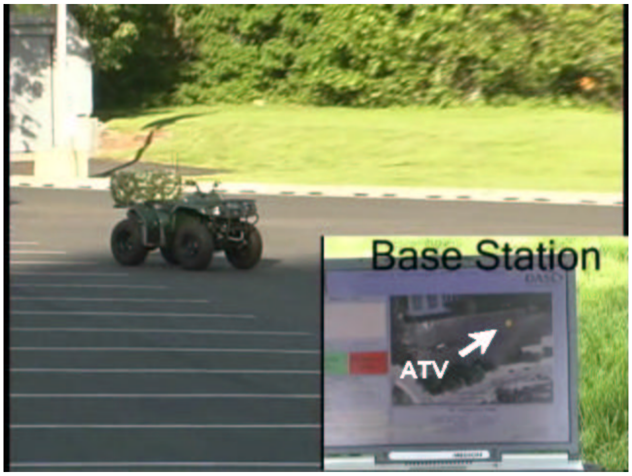

Figure 7: DIAS is retrofitted with electronics and actuators such that it can be operated as a robot or a stock ATV. In robotic mode, DIAS can either be operated with an RC controller or autonomously navigated through GPS waypoints. The bottom right corner shows the base station control application running on a laptop.

analog voltage output by the pot is used to perform PD control of the steering position.

The brakes and throttle are both actuated by servo systems connected in parallel with the existing systems. The servo systems pull on the existing throttle and brake lines, thereby actuating the systems in an open loop manner. The resulting velocity information is gathered via the GPS sensor.

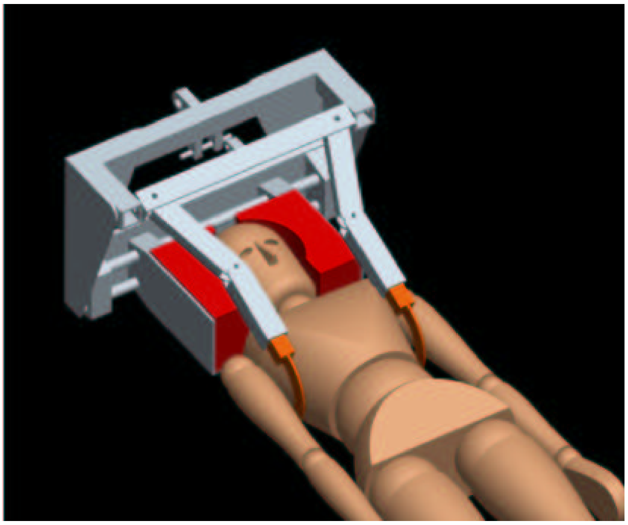

Figure 8: A robotic casualty extraction device. The end effector slips underneath the injured person, supporting the head and neck. Restraints then engage over the shoulders so that the robot can perform an under-the-arm drag.

The shifting system is the only system that removes the stock capability. Shifting works as a “drive-by-wire” system. The shifting arm does not mechanically shift the vehicle into gear but rather sends a signal to the central controller. The controller then commands the servo to the correct position.

DIAS is controlled at two different levels - lower level control on board the vehicle and high level control from a PC base station. On board DIAS is a microcontroller which generates the necessary control signals to drive all of the actuators. It, along with the all of the actuators, is powered through 12 VDC nicad batteries located in the box mounted to the rear rack of the vehicle. The microcontroller also handles any inputs such as steering position, shifting position, or GPS sensor data. Through a wireless RS-232 modem, the microcontroller receives commands from a PC base station.

The PC base station runs a user interface that generates commands for DIAS. From the PC, the operator can switch between, manual control, radio control, or GPS waypoint navigation. Under GPS waypoint navigation, the operator selects waypoints by clicking on a map. Figure 7 shows DIAS performing GPS waypoint navigation. To test the control algorithms, DIAS was given a pattern of GPS points to follow in the form of a “Z”. DIAS successfully navigated all points with a 1 meter accuracy and several hours of operation without refueling/recharging.

Such functionality could be utilized to direct the ATV to victims of a disaster. Equipped with a robotic extraction device, the ATV could bring injured people to safety. DASL has designed such a system, shown in Figure 8.

The combat care extraction arm takes inspiration from a common battlefield extraction technique - the under-the-arm drag. The arm first slides underneath the persons head and neck, providing support. Restraints then engage over the shoulders. When mounted on a vehicle, the person can then be extracted safely.

At the time of this publication, two DIAS robotic ATVs (Yamaha 300CC Grizzly and Polaris 90CC

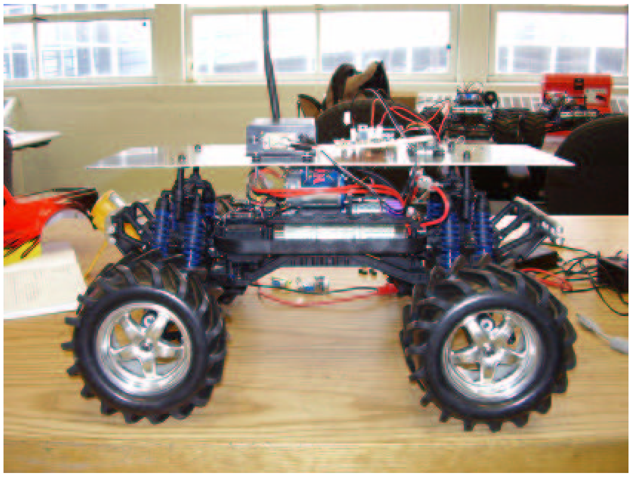

Figure 9: An E-Maxx RC truck retrofitted to be a robotic ground vehicle. The truck can be controlled remotely from a computer and has the hardware to support the addition of many different sensors.

Raptor) have been constructed and tested. Another ATV has been purchased and will be retrofitted to form a group of three ground vehicles. These provide the infrastructure necessary to investigate coordinated robotic missions.

6 Aerial and Ground Robot Teaming

Heterogeneous groups of robots responding to disaster scenarios can increase their effectiveness by sharing information and coordinating their actions. Such robots must themselves possess the ability to carry out basic tasks such as communication, navigation, and collision avoidance [1] [9]. DASL has assembled aerial and ground based testing platforms to investigate these problems.

Figure 10: The SR100 electric helicopter from Rotomotion. The SR100 is sold off the shelf as a robotic platform capable of autonomous hovering and GPS waypoint navigation.

The Rotomotion SR100 electric helicopter pictured in Figure 10 is sold off the shelf as a robotic vehicle. The SR100 is equipped with the accelerometers and IMU's necessary to enable autonomous flight. An 802.11 based telemetry system allows communication with a PC base station from which the aircraft can be remotely controlled. The helicopter can be engaged in either RC control mode or GPS waypoint following mode.

Bombots are modified E-Maxx trucks, currently deployed in Iraq and Afghanistan for locating and detonating improvised explosive devices (IED). While successful, they have limited range and must be operated via line-of-sight. DASL is currently looking at using the SR100 to airlift, airdrop and aerially monitor Bombots. As such, DASL transformed E-Maxx RC trucks into ground based robots as shown in Figure 9.

The drive motors on the E-Maxx were geared down to allow finer motion control. The shocks were changed to provide greater payload capacity. A single board computer and wireless RS-232 modem were placed onboard to allow communication with a base station PC. 4 such platforms have been constructed. Given the ability to distribute these ground based robots over a large area, local missions can be carried out throughout an entire disaster scene.

The SR100 has the ability to air lift the E-Maxx trucks and place them at points of interests. Its 18 lbs payload capacity easily accommodates the 10 lbs E-Maxx. The remaining 8 lbs of payload will be utilized to hold an undercarriage for the E-Maxx trucks. A preliminary design allows the trucks to drive on board the aircraft, secure themselves during flight, and exit by driving off.

7 Conclusions/Future Work

Disaster scenarios demand quick and decisive action from a large, diverse group of workers. Often times the environments are difficult or dangerous for people to work in. First responders can be made effective when equipped with robotic agents for carrying out missions such as reconnaissance, damage assessment, or evacuating the injured. To accomplish these tasks, teams of aerial robots coupled with ground based robots must be employed.

This paper presented an overview of unmanned vehicles, sensors and performance testing for near-Earth missions. A fixed-wing aircraft capable of hovering like a helicopter was presented. Optic flow sensor suites for such an MAV were proposed and tested onboard an indoor aerial robot. A hardware in-the-loop testing facility for MAV sensor suites was described and results from initial tests presented. A ground vehicle for casualty extraction was introduced and GPS waypoint navigation was demonstrated. Finally, a robotic platform for investigating robotic cooperation was assembled.

Current results saw great success in the individual systems operating in typical environments. Future work includes integrating optic flow collision avoidance onto the blackhawk MAV. The control algorithms developed for indoor flight can be used to help blackhawk autonomously navigate during flight in closed quarters. These can be tested on SISTR for refinement before flight. Initial research into cooperative robotic missions must be conducted with the SR100 and E-Maxx trucks. These results can then fuel a larger study in robotic teaming utilizing the DIAS vehicles and existing aerial assets.

References

[1] Batalin, M., Sukhatme, G., Hattig, M., "Mobile robot navigation using a sensor network", *IEEE Int Conference on Robotics and Automation (ICRA)*, New Orleans, LA, V1, pp. 636-641, Apr. 2004.

[2] Blitch, J., "World Trade Center Search-and-Rescue Robots", Plenary Session *IEEE Int Conf Robotics and Automation*, Washington D.C., May 2002.

[3] Casper, J., Murphy, R., "Human-Robot Interaction During The Robot-Assisted Urban Search and Rescue Effort at the World Trade Center", *IEEE Trans. Syst. Man, Cybern. B*, V33, pp. 367-385, June 2003.

[4] Dolan, J.M., Trebi-Ollennu, A., Soto, A., Khosla, P., "Distributed Tactical Surveillance with ATVs", *Proceedings of SPIE*, V3693 AeroSense, Orlando, FL. April 1999.

[5] Fierro, R., Das, A., et al "A Framework and Architecture For Multi-Robot Coordination", *The International Journal of Robotics Research*, V21 N10-11, pp. 977-995, Oct-Nov 2002.

[6] Green, W.E., Oh, P.Y., Barrows, G., "Flying Insect Inspired Vision for Autonomous Aerial Robot Maneuvers in Near-Earth Environments", *IEEE International Conference of Robotics and Automation*, pp. 2347-2352, New Orleans, LA, April 2004.

[7] Murphy, R., et al, "Mobility and sensing demands in USAR", *IEEE Industrial Electronics Conference (IECON)*, V1, pp. 138-142, 2000.

[8] Narli, V., Oh, P.Y.,"A Hardware-in-the-Loop Test Rig for Designing Near-Earth Aerial Robotics",*IEEE International Conference of Robotics and Automation*, pp. 2509 - 2514, Orlando, FL, May 2006.

[9] Ostergaard, E.H., Mataric, M., Sukhatme, G., "Distributed Multi-Robot Task Allocation for Emergency Handling", *IEEE Intelligent Robots and Systems (IROS)*, Maui, Hawaii, V2, pp. 821-826, Oct. 2001.

[10] Rybski, P., Stoeter, S., Gini, M., Hougen, D., and Papanikolopoulos, N.P., "Performance of a Distributed Robotic System Using Shared Communications Channels: A Framework for the Operation and Coordination of Multiple Miniature Robots", *IEEE Transactions on Robotics and Automation*, V18 N5, pp. 713-727, October 2002.

[11] Srinivasan, M.V., Chahl, J.S., Weber, K., Venkatesh, S., Nagle, M.G., Zhang, S.W., "Robot Navigation Inspired By Principles of Insect Vision", *Field and Service Robotics*, A. Zelinsky (ed), Springer Verlag Berlin, NY 12-16.

[12] Vaughan, R.T., Stoy, K., Sukhatme, G.S., Mataric, M., "LOST: Localization-Space Trails for Robot Teams", *IEEE Trans on Robotics and Automation, Special Issue on Multi-Robot Systems*, V18 N5, pp. 796-812, Oct 2002.