Autonomous Robots manuscript No.
(will be inserted by the editor)

CONOPS and Autonomy Recommendations for VTOL MAVs Based on Observations of Hurricane Katrina UAV Operations

Kevin S. Pratt · Robin Murphy · Sam Stover · Chandler Griffin

9/26/2007

Abstract This field study examines VTOL UAV operations conducted as part of an 8 day structural inspection task following Hurricane Katrina in 2005. From the observations of the 32 lights spread over 12 missions, four key findings are identified for CONOPS and the next level of artificial intelligence for rotary-wing UAVs operating in cluttered urban environments. These findings are 1) the minimum useful standoff distance from inspected structures is 2-5m, 2) omni-directional sensor capabilities are needed for obstacle avoidance, 3) GPS waypoint navigation is unnecessary, and 4) that these operations require three operators for one Miniature UAV (MAV). Based on the findings and other observations, a crewing organization and flight operations protocol for UAVs are proposed. Needed directions in research and development are also discussed. These recommendations are expected to contribute to the design of platforms, sensors, and artificial intelligence as well as facilitate the acceptance of UAVs into the workplace.

Keywords UAV Emergency Response · UAV Field Operations · semi-autonomy · Miniature UAVs

Kevin S. Pratt · Robin Murphy · Sam Stover
University of South Florida
4202 E. Fowler Ave., Tampa, FL, 33617
email: kpratt@cse.usf.edu
Tel: (813)-974-3652
Fax: (813)-974-5456

Chandler Griffin
iSensys
925 Golden Beach Boulevard, Indian Harbour Beach, FL 32937
email: chandler@isensys.com
Tel: (321) 750 8342

1 Introduction

After nearly 20 years of using UAVs for long-endurance missions at altitude, the community as a whole is becoming reasonably familiar with the technical and team process requirements for such missions. The recent emergence of miniature UAVs (MAV), also known as micro air vehicles, which we define as a UAV with a wingspan or rotorspan of less than 2m, are introducing new missions and requirements. MAV use, both rotary and fixed wing, in cluttered urban environments is a relatively new development, and as such the technological requirements for these operations are currently ill-defined and poorly understood.

Urban operations involving MAVs are often tactical, such as fire rescue teams inspecting structures, law enforcement conducting surveillance, or military assessing battlefield damage, and thus have a very different set of requirements than traditional strategic UAV operations. In particular, the MAVs are operating in an environment that cannot be guaranteed to be accurately mapped or free of difficult to detect clutter such as power lines, trees, or signage. These operations will be conducted in close proximity to people (including bystanders who may be unaware of the operation) giving rise to important safety concerns. There is usually little to no information about the target for the mission. Finally, to be at all useful for urban operations, the entire system must be man-packable; thus setting strict size and weight limitations with which to fulfill the previous challenges (Murphy, 2004; Garay, 2003).

However, these requirements do not provide an understanding of the possible usages of MAVs, i.e., the concepts of operation (CONOPS), nor identify where advances are needed, both in terms of hardware and autonomy. This impairs the research and development cycle, as technologists may be forced to guess what is needed. Furthermore, the requirements do not substitute for a checklist or protocol on how to use the systems; as noted in McCarley and Wickens (2005), this can lead to avoidable mishaps. The knowledge needed to determine the CONOPS and autonomy needs is generally derived from experience.

Fortunately, our experiences deploying MAVs in the aftermath of Hurricane Katrina provide a corpus of 32 flights, 12 missions conducted over 8 days. During 2005 The Center for Robot-Assisted Search And Rescue (CRASAR) deployed on two occasions to areas of Mississippi and Louisiana effected by Hurricane Katrina. The second deployment was focused on inspecting multi-story commercial buildings for structural damage using a Vertical Take Off and Landing (VTOL) MAV. Based on this second deployment, we propose a broad set Concept of Operations (CONOPS) and autonomy recommendations to guide the development of a base platform, sensors, and software intelligence for general tactical urban operations. These recommendations will be of interest to both researchers and manufacturers, in developing a domain-specific base platform, but additionally as a guide for future research in VTOL UAVs and field operations.

To present and support this set of requirements the remainder of this article is organized as follows. Section 2 discusses previous work in urban MAV operations. Section 3 presents a brief analysis of the domain found in the disaster response operations. Following this Section 4 goes on to cover how data was collected and analyzed as well as the equipment used and how the field team was organized during the research. Finally Section 5 and 6 present the findings and recommendations, respectively, regarding urban MAV operations.

2 Related Work

Previous related research can clearly be delineated into two bodies of work. The first of these is research that deals with the technical challenges of flying MAVs in urban environments, and the second area of research is concerned with the operational issues associated with Unmanned Aerial Vehicles (UAVs). This is the first work to address in tandem the technical as well as the operational requirements of MAV flight operations in cluttered urban environments.

2.1 MAVs in Urban Environments

The work in this article is most closely related to four efforts: the Blackhawk project at Drexel (Green and Oh, 2006), Berkeley Aerial Robotics (BEAR) team (Shim et al., 2005), the AVATAR project from USC (Hrabar et al., 2005), Robotics Institute at CMU (Scherer et al., 2007). These projects address obstacle avoidance in urban environments, but do not address the overall operational needs or larger system design.

One important work dealing with urban MAV operations is the Blackhawk project from the Drexel Autonomous Systems Lab (DASL) (Green and Oh, 2006). This project is focused on using a highly-maneuverable fixed-wing MAV which can operate as a fixed-wing to quickly transition across long distances, but can also go into an autonomous prop hang and operate as a rotary-wing vehicle for inspection tasks. A limitation of this work is that to successfully complete the prop hang maneuver it must have a thrust-to-weight ratio of greater than 1 ($T > W$, $T/W > 1$), which further limits the already stringent payload restrictions on the aircraft. To determine the usefulness of such a vehicle it is important to decide if the gains in loiter time and transition speed outweigh the payload and stability limitations of such a hybrid. Answering this requires we properly characterize these operations according to task demands and operational constraints.

Another work dealing with urban MAV flight ops is from the Berkeley Aerial Robotics (BEAR) team (Shim et al., 2005). This research demonstrated successful autonomous navigation between simulated urban obstacles. This work used multiple scanning lasers attached to a Yamaha RMAX helicopter to detect and avoid the obstacles at the helicopter's altitude. While an important step for vehicle autonomy, this work has limited applicability to the structural inspection, Urban Search And Rescue (USAR), and related MAV flight domains as the RMAX is far from man-packable and current man-packable platforms do not have the payload capacity to mount all the hardware used for this demonstration.

A third project dealing with MAV flight-ops in cluttered urban environments is the AVATAR project from USC (Hrabar et al., 2005). This work combines stereo imaging techniques and optic-flow to navigate a rotary-wing MAV down the center of an urban canyon. This raises a few important questions, namely: 'How prevalent are urban canyons in the operational space?', and 'Is the center of these canyons where we want to be, or does the vehicle need to be closer to one building or another?'.

The most directly related work in urban operations and obstacle avoidance is by Scherer et al. from the Robotics Institute at CMU (Scherer et al., 2007). Using a scanning ladar and an artful 3-D dodger (comprised of competing vertical and horizontal dodger behaviors) their RMAX successfully completed 1000 runs at speeds up to 10 m/s against all types of obstacles from trees and buildings to 6 mm wires. While the ladar and the dodger behavior do provide an elegant solution to the problem, there are two limitations to this work. First, the ladar is too large for a man-packable platform (it is larger by both volume and weight than the entire IP3 platform). Secondly, the ladar system only provides obstacle detection in a forward looking 60° by 40° cone; excellent for forward flight, but insufficient for full three-dimensional coverage.

2.2 Urban CONOPS and Team Practices

There appears to be only one other body of work discussing CONOPS or the operational and team practices used to deploy UAVs during real or simulated events. Hunn et al in (Hunn and Heuckeroth, 2006) propose UAV crew models, but these are for larger, more infrastructure-intensive systems than tactical MAVs. The findings discussed in this article have been reported in a preliminary presentation-only format to AUVSI (Association for Unmanned Vehicle Systems International) in (Pratt et al., 2006). The justification for the human-robot ratio and checklist proposed in this article is more heavily detailed in (Murphy et al., 2007) for the human-robot interaction community; this article is broader in scope and thus is expected to be of use to the larger robotics control, manufacture, and sensor communities.

Papers which cover Human-Robot Interaction (HRI) for UAVs do not discuss actual concepts of operations. The majority of articles deal with interface issues, control and input issues, presenting data to pilots, and the Situation Awareness (SA) capabilities (and deficiencies) this leads to (Calhoun and Draper, 2006; Chadwick et al., 2006; Cooke et al., 2006; Drury et al., 2006; Hottman and Sortland, 2006; Jones et al., 1998; Koeda et al., 2005; Pederson et al., 2006; Quigley et al., 2004, 2005b; Self et al., 2006).

3 Domain Theory

The findings presented in this work are based on observations made during a structural inspection task, which is but one of a larger class of tactical observation missions. This class of missions encompasses street level and neighborhood level observation and intelligence gathering tasks. A few examples of this include: structural safety inspection, wide-area post disaster insurance claims adjustment inspection, path selection for USAR teams through debris fields, USAR victim search, wilderness SAR, and military company or platoon level Intelligence, Surveillance, and Reconnaissance (ISR) missions.

To effectively conduct structural survey missions (or any of these missions), and, more importantly, be able to analyze the platform requirements for such a task, it is crucial to have an initial understanding of the task. Understanding structural survey requires understanding the work domain governing the nature of the operation as well as the key tasks to be performed.

We elicited assistance with the general domain theory of structural survey from a group of 5 structural engineering experts, Scott Nacheman, Dave Hammond, Bill Bracken, Douglas Foutch, and Elizabeth Matlack, who formed our Structural Advisory Board (SAB). The SAB represented academia, industry, and emergency response.

Structural survey operations fall into one of two work domains: *rescue phase* or *recovery phase* (NGA, 1979). During the rescue phase of a response the structural inspection work would be closely tied to specific groups of on-scene responders (man-packable MAVs would likely be organic to responder teams) directly providing structural views to team members for analysis and evaluation. The response phase begins immediately after any disaster with the bulk conducted in the hours and days immediately following, and is typically concluded within one week of an incident. The recovery phase begins once the response phase is concluded and can last months or years depending on the severity of the incident. During the recovery phase structural inspection work by MAVs would most likely be coordinated by property owners, insurance claims adjusters, or building repair contractors. During the less time critical recovery phase operations the data from the MAV would likely not be used directly in the field but transmitted to remote experts in a reachback scenario.

In either work domain, structural inspection will need to provide the following four types of data. Both *plan view* and *elevation views* will need to be provided and labeled consistently with the the terminology employed by the experts viewing the data (responders or structural experts). For both sets of users *wide shots* that help establish overall situational awareness as well as *detailed shots* of specific damaged portions are needed. While video can be useful in establishing the overall scenario, and in framing shots from the still camera, it is the high-resolution still shots which are most useful for sturctural inspection tasks. They obviously contain the most information and detail, and structural inspection presents a static scene to be surveyed, negating any temporal motion advantage presented by video. This initial assumption was later verified by structural experts involved in reachback evaluation of this response.

In the past, structural inspection tasks have typically been accomplished by ground assets or manned aircraft. While each of these methods have their advantages, they also have an overlapping set of limitations. Ground assets have a viewing angle useful only for elevation views of the lower floors, while manned aircraft are best suited for plan views. As shown in Figure 1 this missing segment is the space below FAA regulated airspace, but above what can be achieved with ground-based resources. This space is the target region for MAV operations. In particular rotary-wing MAVs operating in this space can provide all of the data types presented in the task analysis.

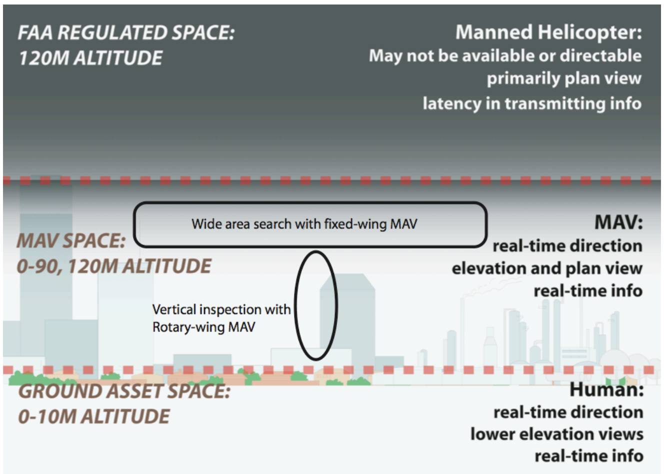


Fig. 1: Vertical profile of an urban structural inspection task overlaid with asset operation zones. Rotary-wing MAVs provide increased capabilities over ground-based assets, and provide these capabilities at a lower cost and with a shorter sensor-analyst path.

4 Data Collection

This section presents the approach and methods used to collect ethnographic (observational) data during this research. First the purpose and nature of the research is described, the flights chronicled, the data collected is discussed, and finally the equipment and team organization used during the research is described.

4.1 Research Overview and Flight Listing

From November 26th - December 5th 2005 a team of researchers from CRASAR deployed to Hancock County, MS to conduct structural surveys of multi-story commercial structures in Biloxi and Gulfport, MS. During this time the team conducted 12 different missions at 7 different sites with a total of 32 flights during all missions. Figure 2 shows the locations of these flights and Table 1 provides the dates and locations of the different missions.

Fig. 2: Map of Biloxi, MS showing locations of surveyed structures. Map © Google, 2006.

Table 1: Locations and dates for survey missions

Flight Location	Dates Flown
Hancock County EOC	11/30/2005 12/3/2005
Casino Magic	11/29/2005 12/2/2005
Grand Casino Gulfport	11/30/2005
Hard Rock Casino	11/30/2005 12/2/2005
Isle of Capri	12/1/2005
President Casino Barge	12/1/2005 12/3/2005
1550 Beach Blvd.	12/2/2005 12/3/2005

4.2 Data Collection

During each mission (which included all consecutive flights at one location) several pieces of data were collected. These included pre and post-flight meteorological data sets, flight team voice recordings, flight team debriefs, video streams from 4 video cameras, and still pictures from the payload camera. This data, particularly the debriefings and the flight video, was then reviewed and analyzed to derive the findings regarding the operational and technical requirements for MAV operations in cluttered urban environments. In this analysis the team debriefings were used as the initial results and the video and other data sets were then used to corroborate or amend the team's comments about flight conditions and vehicle actions. Though not corrected directly in the field, another important source of data was feedback from the SAB. This feedback was useful not only in honing our methods to produce the most useful results, but more importantly to verify that we were in fact producing useful results in the first place, and thus that any CONOPS or autonomy findings were indeed legitimate.

4.3 Equipment and Team Organization

The structural survey missions which form the foundation of this work were evaluations of multiple independent multi-story commercial structures approximately 90 days after Hurricane Katrina made landfall in the Gulf Coast region. The primary focus of these missions was recovery-phase single-structure vertical inspections and thus the most effective platform for this work was a man-packable rotary-wing MAV.

For these missions the Imaging Platform 3 (IP3) MAV was selected. The IP3 is a commercially available platform produced by iSensys, an Institute for Safety, Security, and Rescue Technology (ISSRT) NSF-Industry center member company. The IP3 loosely based on the Mikado Logo-14 and has been modified for stability, run time, and payload control. It is an electrically powered helicopter which has a 42 V 4200 mAh Lithium-Polymer battery pack, a 1.40 m rotorspan, 1 kg of payload capacity, a fixed pilot-view camera to provide increased situational awareness to the pilot, a 15 minute flight endurance, a 25 cm 3-axis infinite rotation gimbal, and can hold up to 8 separate imaging systems and up to 6 2.4 GHz wireless video transmitters.

In addition to the IP3 both the pilot and the mission specialist were outfitted with 72 MHz wireless controllers, 2.4 GHz wireless video receivers, Heads-Up Displays (HUDs), and video cameras to record all received data. Figure 3 illustrates all of this equipment.

To operate the IP3 system a three-person flight team was used. The flight team consisted of the flight director, who was responsible for team safety, maintaining overall situation awareness, and for the mission as a whole, the pilot who was responsible for the aircraft, and the mission specialist who was responsible for the payload and gathering the data targeted during the mission. Each team member was responsible for a different level of situational awareness and had an inversely proportional degree of computer mediation (refer to Section 5.4 for more discussion of the operator:vehicle ratio). For safety and observability reasons all flights during these deployments were conducted within Line of Sight (LOS) of the flight team.

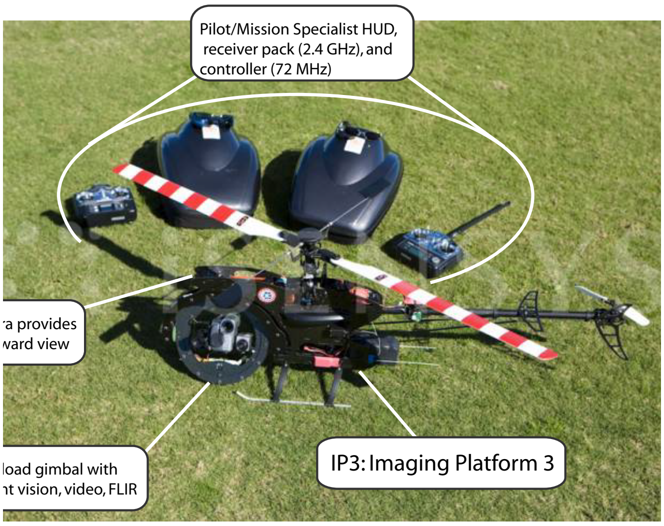
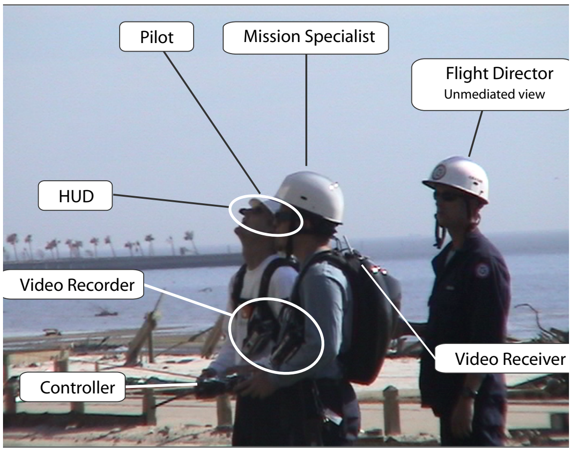


Fig. 3: iSensys IP3 MAV plus pilot and and mission specialist operational equipment.

Figure 4 shows the IP3 equipment in use on the flight team, as well as the team organization and responsibilities during a mission.

5 Findings

Based on the flight and observational data, four primary CONOPS and autonomy findings are identified for VTOL UAVs conducting inspection-type tasks in cluttered urban environments. The observations suggests that a standoff range of 2-5m is the minimum standoff distance required by these operations (there is no operational requirement for MAVs to operate any closer than this to the target structure), that omni-directional obstacle avoidance is necessary to move MAVs from teleoperated to semi-autonomous capabilities, GPS waypoint navigation is *not* a required feature for structural inspection tasks, and that to safely and effectively conduct inspection missions a three-person flight team is required for each MAV.



(a) Flight Team with equipment

(b) Flight Team with mission responsibilities noted

Fig. 4: Flight team with equipment noted and with team member responsibilities.

5.1 Vehicle Standoff

The first finding is that 2 to 5m appears to be a sufficiently close standoff distance for the MAV. In a structural inspection task the clarity and detail of the images produced are crucial to successful analysis by structural experts. Qualitatively this requires the MAV to be as close as possible to the structure being inspected. Given the power of today's commonly available optics the reality is that there is an easily achievable minima for this requirement. During these flights the IP3 was outfitted with a simple consumer-grade Commercial Off The Shelf (COTS) 5 Megapixel digital camera. Even with this entry-level COTS solution the images taken from this 2-5 m distance had ample detail and clarity for structural experts to perform their analysis. By moving to an improved optics package this distance could be correspondingly increased (the IP3 gimbal was designed to support an Canon EOS 5D camera body and a telephoto lens. The 5D shoots 12.8 megapixel images).

This finding has clear implications for control. First, the MAV may be operating in a region where GPS is denied; that is, the signals are blocked or multi-pathed due to the urban structures. Second, this is a region where the effects of wind and rotors so near structures has not been explored. This means more research is needed to produce the optimal platform shape and controls, as well as gimbal response times. It is also relevant to the obstacle avoidance discussion presented below. Whatever obstacle avoidance methodology is selected, be it laser, ladar, or optical, it only requires the ability to clear this 2-5m volume around the craft (effectively treating the vehicle as a single point, or a uniform sphere), instead of needing to be aware of the precise shape of the craft and bringing it within centimeters of given portions of the craft.

5.2 Obstacle Avoidance

The second finding is that obstacle avoidance must be provided for the complete envelope surrounding the MAV. While it is certainly most intuitive for pilots to approach targets head on, this serves as no indication of the only origin for flight obstacles; quite contrarily in fact, flight obstacles can approach a VTOL from any angle. During the Biloxi flights the pilot had to be aware of and avoid obstacles encroaching on the aircraft from all angles, just as any semi-autonomous MAV would need to be. Figure 5 shows the most complex environments encountered with the IP3. In this image the IP3 was flying into a building to image a structural beam that had been compromised by repeated impacts from a barge that ended up resting on the structure. Above the IP3 is a solid steel ceiling as well as hanging wires and ceiling tile supports, below it are caution tape as well as a 2x4 barrier, and encroaching from multiple sides are a trash compactor and several structural steel beams. Additionally the hanging ceiling supports and the caution tape were light enough that they were moving in the wind and the rotorwash of the IP3. At other locations obstacles such as trees, flagpoles, electric and phone lines, building overhangs, and damaged building superstructure were all present in the flight path. While the vehicle will not need to come within 2-5 m of its intended target, any semi-autonomous MAV will need to be able to successfully detect and avoid all types of obstacles approaching from all angles.

During recent discussions of introducing UAVs into the National Airspace System (NAS) the ability to Detect, Sense, and Avoid (DSA) non-cooperating aircraft has been often discussed as a prerequisite for this introduction (Weibel and Hansman, 2004; Grilley, 2005; Weibel and Hansman, 2005). It is important to note that the obstacle avoidance capability proposed here is different than DSA. In fact for MAV systems operating below 120m Above Ground Level (AGL) (below minimum height for manned aircraft not engaged in landing or takeoff operations) and within LOS of the flight team omni-directional obstacle avoidance is more important than DSA.

Fig. 5: The IP3 flying into a building to image concealed damage.

5.3 GPS Waypoint navigation

In existing autonomous UAVs GPS is a very common navigation solution. As researchers seek to develop semi-autonomous MAVs GPS is a clear choice for inclusion in these systems; but before extensive effort is invested it is important to consider if this is an appropriate step.

For MAVs used in structural survey tasks GPS waypoint navigation would not be a commonly used feature and should not be a central development task for such systems. In this work domain inspection tasks are very much human-in-the-loop tasks; not only to maintain operator, bystander, and vehicle safety but also to evaluate the results in real-time. As it is by necessity a human-in-the-loop task and operators are already evaluating the returning data streams, they will inevitably see new things which were occluded from their ground-based preflight positions, modify the order tasks will be addressed, or even simply require the MAV to stay on a given task for longer than anticipated. In short, the Biloxi flights showed that structural survey work is a very dynamic task and that flight plans regularly changed as soon as the IP3 took off. To the degree the flight plan changes once airborne navigating to a fixed set of GPS coordinates rapidly becomes not useful. Figure 6 shows a case where it was not possible to determine the nature of the damage from the ground during the pre-flight, and it had to be evaluated from the helicopter once the flight had begun. The damage could have been superficial or non-existent, not requiring examination with the IP3, or it could have been very severe and require immediate and thorough evaluation.

Fig. 6: The President Casino Barge shows an example of why in-flight redirects were so common. The nature and extent of the damage could not be evaluated beforehand and had to be evaluated in-flight to determine what required further documentation and analysis.

The second reason why GPS navigation was found to be undesirable is the overhead. In UAV systems, particularly fixed-wing variants, GPS waypoint navigation is a critical tool and, if the flight plan changes, the waypoints can be modified on the ground station and the new set uploaded. This presents two problems when applied to MAVs in a structural inspection-type task. The first is that our average flight time was between 10 and 15 minutes, so any update process that takes 1 minute, or even 30 seconds consumes a significant portion of the flight time with unnecessary overhead. The second problem is that changes of this nature would require some form of control station computer, and for a system to be usable it must be entirely man-packable; operators in this work domain are mobile during flights, they are not seated at a computer terminal.

5.4 Operator:Vehicle Ratio

The fourth finding is that a 3:1 operator to vehicle ratio appears to be the baseline and may be difficult to reduce. It is both normal and natural to want to make the operator:vehicle ratio as low as possible. For both safety and effectiveness reasons working with a semi-autonomous MAV to conduct urban flight operations requires a minimum of three operators to one vehicle. While conducting flight-ops in Biloxi, an effective, safe three-man flight team emerged: Pilot, Mission Specialist, and Flight Director. Refer to Section 4.3 for a description of these roles and their responsibilities during flight operations.

In hindsight, these roles were seen in prior fieldings of both fixed- and rotary-wing UAVs during the Hurricane Katrina response, but were not identified at that time. This also indicates that the findings are not platform or interface specific.

Figure 7 suggests that these roles cannot be combined to produce a 2:1 or 1:1 operator:vehicle ratio without risking a severe degradation of performance due to the lack of informational overlap between the three roles. While all team members are looking at the same scene, each member sees something significantly different. From the left, the mission specialist sees only what is presented through the viewfinder and is functionally oblivious to outside influences, the pilot divides his attention between the MAV and the supplementary HUD and lacks the cognitive bandwidth to track anything else, and finally the flight director is the only team member which can be relied on to be aware of the MAV, the survey site, and the other team members.

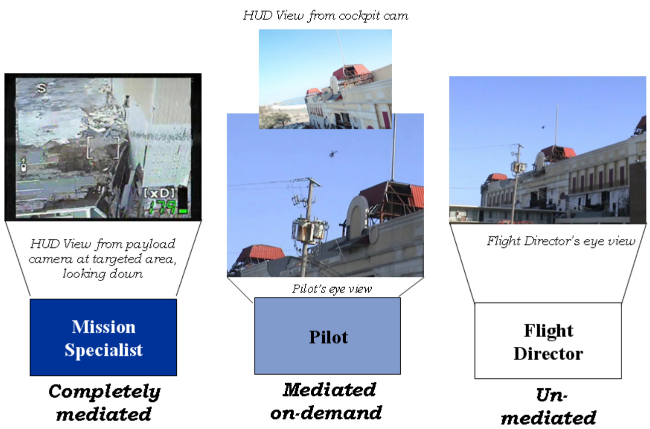


Fig. 7: The three different views of the flight-team members. Each team member has a different focus and a different degree of computer mediation, making role combination difficult and undesirable.

5.5 Additional Findings

In addition to the four primary findings, there are several other important observations to be drawn from these flights. For safety reasons all flights must be conducted within Line of Sight (LOS) (providing the proxy replacement for the DSA discussed previously in subsection 5.2, but the flight director must be aware of all people in the flight area, and during an emergency the pilot must be able to safely guide the MAV to a landing zone), and thus to survey multiple sides of a building requires multiple shorter flights, rather than a single combined flight for an entire building. As long as the MAV can be rapidly refueled (as with battery change for an electric MAV) the total system endurance becomes less of a factor.

Another notable lesson was that to be an effective field team one of the team members must have some domain expertise to help guide and direct the team in the field. Particularly in a recovery-phase structural survey task with reachback to remote structural experts it was crucial to have one team member (the flight director in this case) who had formal structural training and could serve as an intermediary/translator between the two groups and as an on-site expert to direct the survey missions.

The focus of this set of inspections was commercial structures, all but one of which were steel frame construction with varying degrees of additional metal in the siding and roofing materials. Unsurprisingly, using consumer grade wireless communications equipment in this steel jungle led to very noticeable interference and signal loss problems. It is a somewhat obvious point of consideration, but any professional-grade MAV system designed to operate in urban environments must take this into account.

A final lesson to consider is that site access was a very important consideration during these structural inspection tasks. Site access includes both MAV landing zones as well as personnel positioning during the flights. Due to both safety concerns and the difficulty of movement both near compromised structures and through such a wide-area disaster made both good landing zones and team positions difficult to come by, and those that were available were often far away and/or suboptimal. In short, compared to a typical hobby RC pilot these flights were typically launched and recovered from smaller, more confined landing zones and conducted at longer standoff ranges. To address this problem, solutions that can extend the pilots effective operating range and give them increased control of the MAV are needed.

6 Recommendations

Based on the above findings, two categories of recommendations emerge: one on general flight operation and crew organization and the second on needed research and development.

6.1 Flight Operations and Crew Organization

A three-person flight crew is recommended. The Pilot is responsible for the flight and flight worthiness of the platform. The Pilot should be highly trained and experienced. The Mission Specialist is responsible for the payload and actually collecting (or supervising collection) of the data. It is desirable for the Mission Specialist to be a subject matter expert so as to ensure the most useful data is collected. The Flight Director is responsible for overall safety of the public, the team, and the robot (in order of priority). The Pilot and Flight Director should be well aware of civilian airspace regulations, at the level of FAA Private Pilot's Written Exam; the Mission Specialist as a subject matter expert may be recruited from the emergency responders and thus it would be hard to make such a requirement apply to that role.

It is recommended that the flight crew to follow a four step flight operations procedure consisting of *site selection*, *planning and rehearsal*, *flight*, and *data review*. The procedure is:

- Safety review of site and landing zones selection. The Flight Director should be in charge of site selection and primary staging of the equipment, though all crew members are involved. Site selection consists of determining adequate launch and landing zones that provide a line-of-sight viewpoint to the MAV over the desired areas around the structure, confirming restricted access from bystanders, and projecting a flight path that reduces the possibility of flying near civilians.
- Planning and rehearsal. After the site selection, the Pilot should lead a short flight planning and rehearsal session at the landing zone. Any potential flight problems are discussed, such as flying into the sun or in the interior of structures, and *safe zones* of operation would be established. Likewise, any potential *team access hazards* should be identified by the Flight Director and mitigated; for example, by providing personal floation devices when working on piers. The platform and payloads checks would be conducted by the Pilot and Mission Specialist, along with a scan of the airspace for other aircraft.
- Flight. The flight path itself will be dynamically generated as the Mission Specialist begins to view the damage. The Mission Specialist and Pilot stand in easy communications range and cooperatively find the right altitudes and angles for collecting the requisite data. In the case of any sort of anomaly, such as unexpected high turbulence or a temporary loss of communications, the vehicle would be grounded. Likewise, the MAV should be immediately grounded of the MAV if a bystander or a manned aircraft are spotted by the Flight Director or any member of the team.
- Data review. Once on the ground, a review would be conducted of video and stills recorded in-flight with the structural expert. If any data was missing or needed a better photograph, the flight should be reflown.

The latter three steps would be repeated for each face of the structure, with the first flight capturing a plan view in addition to the elevation view of the first face.

6.2 Directions for Autonomy

We recommend research and development in controls, semi-autonomy, mixed-team processes, and better interfaces, rather than more traditional GPS waypoint autonomy, in order to build low-cost, effective systems.

The finding of the close proximity of the MAV to urban structures for this domain presents a challenging, gusty environment that requires more research. The flight controls and gimbal response must be suitable to handling and responding quickly enough in this regime. Collision avoidance is particularly challenging due to proximity to structures and the ground, which implies a rapid sense-respond cycle, and to the nature of flights, where a sudden gust may significantly move the vehicle in any direction.

We recommend a focus in semi-autonomy versus full taskable autonomy (e.g., "go to locations X, Y, Z, take pictures at each, and land"). Several findings support this. We have observed that this is a domain where a human is expected to observe the results in real-time for scene interpretation. Likewise, a human is needed to direct the dynamic flight planning. Finally, a human is likely to be mandated to stay involved for safety reasons; it is difficult to see how the roles of Pilot, Mission Specialist, and Flight Director could be attained by a single agent, human or robotics. Specifically, we recommend focusing on i) guarded motion, where a human directs the mission, but the robot takes over the Pilot role and 2) cooperative sensing, where the robot assists the human in ensuring sensor coverage.

The recommendation of a focus on semi-autonomy is coupled with the recommendation to expand research in mixed-team (humans and robots) processes. The identification of three distinct roles suggests at least two directions for research in mixed-team processes. One direction is on how to safely reduce the high operator:vehicle ratio, particularly as increases in autonomy will permit sharing or transfer of the Pilot role. The second is how to optimize team processes, especially if the Mission Specialist is a "pick up" member of team, added to the team at the disaster. Adding a new person to a team typically retards overall performance as the person comes up to speed in the task and also establishes appropriate relationships and work practices with teammates. Research in protocols and hasty training may obviate the costs of the Mission Specialist as an outsider.

Clearly, better human-robot interfaces are needed and are recommended for further research. We believe the roles needed to field a safe team are independent of interfaces due to the severe differences in viewpoints. However, the general workload on the mediated Pilot and Mission Specialist could likely be improved by better interfaces (and increased autonomy).

7 Summary and Future Work

During 2005 the Center for Robot-Assisted Search and Rescue spent 8 days surveying damage from Hurricane Katrina to 7 multi-story commercial structures in Biloxi and Gulfport. The output of 32 flights was examined by an advisory board comprised of structural inspection experts from industry, emergency response, and academia. The effort established the general domain theory for structural inspection using UAVs and provided a basis for extracting key findings that should help direct the future development of semi-autonomous MAV systems for structural survey operations in cluttered urban environments. We found that 2-5 m is sufficiently close to any target to obtain the necessary images, omnidirectional obstacle avoidance is a necessary feature of any semi-autonomous system, GPS waypoint navigation is not necessary for these operations, and that to safely and effectively conduct these missions three operators are required for one vehicle. The findings led to a recommended crewing organization and flight operations protocol, as well as directions for future research and development of semi-autonomous MAVs.

To help solve some of the challenges, CRASAR is pursuing two of the three research directions for semi-autonomy: obstacle avoidance and team processes. To address the obstacle avoidance needs, work is currently being done in real-time wire detection algorithms Kasturi and Camps (2002), as well as the development and flight testing of a combined CMOS/FPGA embedded vision sensor for use in mobile applications. Team processes and operator interaction deficits are being explored as well.

Acknowledgments

This material is based upon work supported by the National Science Foundation under SGER CMS grant 0554059. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors thank the Structural Advisory Board; Scott Nacheman, Dave Hammond, Bill Bracken, Douglas Foutch, and Elizabeth Matlack, who provided feedback on the data collected.

References

A. William Evans, I., Hoeft, R.M., Jentsch, F., Rehfeld, S.A., Curtis, M.T.: Exploring human-robot interaction: Emerging methodologies and environments. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 345–355. JAI (2006)

Blackburn, M.R., Everett, H.R., Laird, R.T.: After action report to the joint program office: Center for the robotic assisted search and rescue (crasar) related efforts at the world trade center. Tech. rep., SPAWAR Systems Center San Diego (2002)

Bland, G., Coronado, P., Miles, T., Bretthauer, J.P.: The aeros project: Experiments with small electric powered uavs for earth science. In: Infotech @ Aerospace. Arlington, VA (2005)

Burke, J.L.: Moonlight in miami: A field study of human-robot interaction in the context of an urban search and rescue disaster response training exercise. Master's thesis, University of South Florida, 4202 E. Fowler Ave. Tampa, FL 33620 (2003)

Calhoun, G.L., Draper, M.H.: Multi-sensory interfaces for remotely operated vehicles. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 149–165. JAI (2006)

Casper, J.: Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center. Master's thesis, University of South Florida, 4202 E. Fowler Ave. Tampa, FL 33620 (2002)

Chadwick, R.A., Pazuchanics, S.L., Gillan, D.J.: What the robot's camera tells the operator's brain. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 373–384. JAI (2006)

Clancey, W.J.: Observation of Work Practices in Natural Settings, pp. 127–145. Cambridge University Press (2002)

Cooke, N.J., Pederson, H.K., Connor, L., Gorman, J., Andrews, D.: Acquiring team-level command and control skill for uav operation. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 285–297. JAI (2006)

Drury, J.L., Riek, L., Rackliffe, N.: A decomposition of uav-related situation awareness. In: 1st Annual Conference on Human-Robot Interaction, pp. 88–94. Salt Lake City, UT (2006)

Gage, A., Murphy, R.R., Rasmussen, E., Minten, B.: Shadowbowl 2003 [simulated mass-casualty exercise]. IEEE Robotics & Automation Magazine **11**(3), 62–69 (2004). DOI 10.1109/MRA.2004.1337827

Garay, R.A.: Marine corps systems command liaison team: Field report central irag, 20 april to 25 april 2003. Field report, United States Marine Corps (2003)

Gourley, S.: Raven uav. Army Magazine **55** (2005)

Green, W., Oh, P.: Autonomous hovering of a fixed-wing micro air vehicle. In: Proceedings of the IEEE International Conference on Robotics and Automation, 2006. ICRA 2006., pp. 2164–2169 (2006)

Grilley, D.E.: Resolution requirements for passive sense and avoid. Tech. rep., Alion Science and Technology, 3592 Collins Ferry Rd. Ste 180, Morgantown, WV, 26505 (2005)

Holland, G.J., Webster, P.J., Curry, J.A., Tyrell, G., Gauntlett, D., Brett, G., Becker, J., Hoag, R., Vaglienti, W.: The aerosonde robotic aircraft: A new paradigm for environmental observations. Bulletin of the American Meteorological Society **82**(5), 889–902 (2001)

Hottman, S.B., Sortland, K.: Uav operators, other airspace users, and regulators: Critical components of an uninhabited system. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 71–88. JAI (2006)

Hrabar, S., Sukhatme, G., Corke, P., Usher, K., Roberts, J.: Combined optic-flow and stereo-based navigation of urban canyons for a uav. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005. (IROS 2005), pp. 3309–3316 (2005). DOI 10.1109/IROS.2005.1544998

Hunn, B.P.: Video imagery's role in network centric, multiple unmanned aerial vehicles (uav) operations. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 179–192. JAI (2006)

Hunn, B.P., Heuckeroth, O.H.: A shadow unmanned aerial vehicle (uav) improved performance research intergration tool (imprint) model supporting future combat systems. Tech. Rep. ARL-TR-3731, Army Research Laboratory (2006)

Jones, H.L., Frew, E.W., Woodley, B.R., Rock, S.M.: Human-robot interaction for field operation of an autonomous helicopter. In: Choset, H.M. (ed.) Mobile Robots XIII and Intelligent Transportation Systems, vol. 3525. SPIE (1998)

Kasturi, R., Camps, O.I.: Wire detection algorithms for navigation. Tech. Rep. 20020060508, Nasa Ames Research Center (2002)

Knabb, R.D., Rhome, J.R., Brown, D.P.: Tropical cyclone report: Hurricane katrina: 23-30 august 2005. Tech. rep., National Hurricane Center (2006)

Koeda, M., Matsumoto, Y., Ogasawara, T.: Annotation-based rescue assistance system for teleoperated unmanned helicopter with wearable augmented reality environment. In: Safety, Security and Rescue Robotics, Workshop, 2005 IEEE International, pp. 120–124 (2005). DOI 10.1109/SSRR.2005.1501250

Lee, W., Ryu, H., Yang, G., Kim, H., Park, Y., Bang, S.: Design guidelines for map-based human-robot interfaces: A colocated workspace perspective. In: International Journal of Industrial Ergonomics, vol. 37, pp. 589–604. Elsevier (2007)

Lundberg, C., Christensen, H.I., Hedstrom, A.: The use of robots in harsh and unstructured field applications. In: IEEE International Workshop on Robot and Human Interactive Communication, 2005, ROMAN 2005, pp. 143–150 (2005). DOI 10.1109/ROMAN.2005.1513771

McCarley, J.S., Wickens, C.D.: Human factors implications of uavs in the national airspace. Tech. Rep. AHFD-05-5/FAA-05-1, University of Illinois Institute of Aviation: Aviation Human Factors Division, Savoy, IL (2005)

McGeer, T., Vagners, J.: Wide-scale use of long-range miniature aerosondes over the world's oceans. In: Proceedings of AUVSI 26th Annual Symposium. Association for Unmanned Vehicles Systems International (1999)

McHuch, V.M., Ince, B.S., Blethen, G.E., Harden, C.S., Schafer, R.J., Harper, S.E., Arnold, P.D., Thomas, M.A.: Update on an unmanned aerial vehicle (uav) payload for detectinon, identification, and acquisition of vaprs of toxic substances and their precursors. In: ISIMS 2004 13th International Conference on Ion Mobility Spectometry (2004)

Metni, N., Hamel, T.: A uav for bridge inspection: Visual servoing control law with orientation limits. Automation in Construction **17**(1), 3–10 (2007). URL http://www.sciencedirect.com/science/article/B6V20-4NVK1SN-1/2/5d6e8e3ac49192368146a54222e7c23c

Micire, M.: Analysis of the robotic-assisted search and rescue response to the world trade center disaster. Master's thesis, University of South Florida, 4202 E. Fowler Ave. Tampa, FL 33620 (2002)

Murphy, R.R.: Human-robot interaction in rescue robotics. Systems, Man and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on **34**(2), 138–153 (2004). DOI 10.1109/TSMCC.2004.826267

Murphy, R.R.: Fixed and rotary-wing uavs at hurricane katrina. In: Video Proceedings of IEEE International Conference on Robotics and Automation, 2006, ICRA 2006 (2006)

Murphy, R.R., Burke, J.L.: Up from the rubble: Lessons learned about hri from search and rescue. In: Proceedings of the 49th Annual Meeting of the Human Factors and Ergonomics Society (Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ)

Murphy, R.R., Pratt, K.S., Burke, J.L.: Crew roles and operational protocols for rotary-wing micro-uavs in close urban environments. Tech. Rep. CRASAR-TR2007-1, Center for Robot-Assisted Search And Rescue (CRASAR), 4202 E. Fowler Ave. Tampa, FL 33620 (2007)

Murphy, R.R., Steimle, E., Cullins, C., Pratt, K.S., Griffin, C.: Cooperative damage inspection with unmanned surface vehicle and micro aerial vehicle at hurricane wilma. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, (IROS06) (2006)

NGA: Comprehensive emergency management: A governors guide. Tech. rep., National Governors' Association (1979)

Oh, P.Y., Green, W.E., Barrows, G.: Neural nets and optic flow for autonomous micro-air vehicle navigation. In: Proceedings of the 2004 ASME International Mechanical Engineering Congress and Exhibition (IMECE04) (2004)

Orr, M.W., Rasmussen, S.J., Karni, E.D., Blake, W.B.: Framework for developing and evaluating MAV control algorithms in a realistic urban setting. In: Proceedings of the 2005 American Control Conference, pp. 4096–4101 (2005). DOI 10.1109/ACC.2005.1470619

Pachter, M., Chandler, P.R., Darbha, S.: Optimal sequential inspection. In: 45th IEEE Conference on Decision and Control, pp. 5930–5934 (2006). DOI 10.1109/CDC.2006.377720

Pederson, H.K., Cooke, N.J., Pringle, H.L., Connor, O.: Uav human factors: Operator perspectives. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 21–33. JAI (2006)

Pratt, K.S., Murphy, R.R., Stover, S., Griffin, C.: Requirements for semi-autonomous flight in miniature uavs for structural inspection. In: Proceedings of Autonomous Unmanned Vehicles Sytems International (AUVSI 2006) (2006)

Quigley, M., Barber, B., Griffiths, S., Goodrich, M.A.: Towards real-world searching with fixed-wing mini-uavs. In: Proceedings of 2005 IEEE/RSJ Conference on Intelligent Robots and Systems, (IROS 2005). Edmonton, Alberta, Canada (2005a)

Quigley, M., Goodrich, M.A., Beard, R.W.: Semi-autonomous human-uav interfaces for fixed-wing mini-uavs. In: Proceedings of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, (IROS 2004). Sendai, Japan (2004)

Quigley, M., Goodrich, M.A., Griffiths, S., Eldgredge, A., Beard, R.W.: Target acquisition, localization, and surveillance using a fixed-wing mini-uav and gimbaled camera. In: Proceedings 2005 IEEE International Conference on Robotics and Automation, (ICRA 2005). Barcelona, Spain (2005b)

Raffetto, M.A.: Unmanned aerial vehicle contributions to intelligence, surveillance, and reconnaissance missions for expeditionary operations. Master's thesis, Naval Postrgraduate School, Monterey, CA (2004)

Scherer, S., Singh, S., Chamberlain, L., Saripalli, S.: Flying fast and low among obstacles. In: Proceedings 2007 IEEE International Conference on Robotics and Automation, (ICRA 2007) (2007)

Schneider, W.: Defense science board study on unmanned aerial vehicles and uninhabited combat aerial vehicles. Tech. rep., Office of the Under Secretary of Defence For Acquisition, Technology, and Logistics (2004)

Schreckenghost, D.K.: Checklists for human-robot collaboration during space operations. In: Human Factors and Ergonomics Society Annual Meeting, vol. 43, pp. 46–50 (1999)

Self, B.P., Ercoline, W.R., Olson, W.A., Tvaryanas, A.P.: Spatial disorientation in uninhabited aerial vehicles. In: Cooke, N.J., Pringle, H.L., Pederson, H.K., Connor, O. (eds.) Human Factors of Remotely Operated Vehicles, vol. 7, pp. 133–146. JAI (2006)

Shim, D.H., Chung, H., Kim, H.J., Sastry, S.: Autonomous exploration in unknown urban environments for unmanned aerial vehicles. In: Proceedings of the AIAA Conference on Guidance, Navigation, and Control, 2005. AIAA GN&C 2005. (2005)

Vicente, K.J.: Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work. LEA, Inc. (1999)

Weibel, R.E., Hansman, R.J.: Safety considerations for operation of different classes of uavs in the nas. In: AIAA 4th Aviation Technology, Integration, and Operations (ATIO) Forum. AIAA (2004)

Weibel, R.E., Hansman, R.J.: Safety considerations for operation of unmanned aerial vehicles in the national airspace system. Tech. Rep. ICAT-2005-1, MIT International Center for Air Transportation, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 02139 (2005)

Yi, H., Song, B., Ji, D., Yu, T.: Experiment research on situation awareness of the operators for unmanned aerial vehicle. In: Computational Intelligence and Security, 2006 International Conference on, vol. 2, pp. 1225–1228 (2006). DOI 10.1109/ICCIAS.2006.295251

Zufferey, J.C., Floreano, D.: Toward 30-gram autonomous indoor aircraft: Vision-based obstacle avoidance and altitude control. In: Robotics and Automation, 2005. ICRA 2005. Proceedings 2005 IEEE International Conference on (2005)