Analysis of VTOL MAV Use During Rescue and Recovery Operations Following Hurricane Katrina

by

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Dedication

To my parents and my sisters for their ardent, unfailing, and utterly genuine support. This thesis is one of the many things that would not have been possible without you.

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And also a special thanks to the entire crew of the Hancock County, Mississippi EOC. Even though they themselves were still living in a muddy field three months after the hurricane hit, everyone there was enormously gracious in providing everything including hot food, internet access, a place to park our RV, and everything in between.

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ABSTRACT

There can be little doubt that Hurricane Katrina will always be remembered for the damage and devastation it caused. But it also provided the first opportunity for MAVs to be used and evaluated during Search and Rescue (SAR) as well as recovery operations. Researchers from The Center for Robot-Assisted Search And Rescue (CRASAR) made two separate deployments to areas affected by Hurricane Katrina: one during initial SAR operations and a second deployment during recovery operations 90 days later. Using data and observations from both of these deployments, this work draws four key findings about semi-autonomous Miniature UAV (MAV) operations in urban environments. These findings are intended to guide future MAV research as well as serve as a roadmap for the evolution from semi-autonomous to fully autonomous MAV capabilities. These findings are as follows: the minimum useful standoff distance from inspected structures is 2-5 m, omni-directional sensor capabilities are needed for obstacle avoidance, GPS waypoint navigation is unnecessary, and that these operations currently require three operators for one MAV.

Chapter 1

Introduction

On August 29^{th}, 2005 Hurricane Katrina ravaged the coastal regions of Louisiana and Mississippi. Though the numbers would not be finalized for many months, it was the deadliest and costliest Atlantic hurricane in nearly 80 years [20]. In the days and months following, hundreds of local, state, and federal organizations and thousands of people were mobilized to respond to the disaster. One of these organizations was The Center for Robot-Assisted Search And Rescue (CRASAR) from the University of South Florida. One team from CRASAR was on standby when the storm hit, and was deployed to Bay St. Louis and Pearlington, MS to help with emergency response from August 30^{th} through September 1^{st}. Ninety days later a second CRASAR team deployed to Biloxi and Gulfport, MS to conduct structural survey operations in support of ongoing recovery work.

This first deployment by the CRASAR team was the first use of Miniature UAVs (MAVs) during a live emergency response and these operations combined constitute the bulk of known MAV operations for emergency response, and practically all of the flights conducted to date with scientific research in mind.

As these are some of the earliest operations of their kind, these flights contain many layers of data regarding MAV flights. One of the most important, however, is what can be learned about MAV flight in cluttered urban environments. Unmanned Aerial Vehicles (UAVs) have been around for at least 20 years, but thus far they have been primarily large fixed-wing vehicles flown at altitude conducting Intelligence, Surveillance, Target Acquisition, and Reconnaissance (ISTAR) operations. The use of MAVs, particularly rotary-wing Vertical Take Off and Landing (VTOL) aircraft, at low altitude in cluttered urban environments is a new style of operations with very little published literature discussing methodologies and requirements for such operations.

1.1 Hurricane Katrina

Hurricane Katrina made its first landfall at the Miami-Dade / Broward County border in southern Florida at 2230 UTC on August 25th, but it was not until its second and third landfalls in Louisiana and Mississippi at 1110 and 1445 UTC on August 29th that it wreaked its devastation. While transiting across the Gulf, Katrina generated sustained winds of 280 kmh (175 mph) with a minimum central pressure of 902 mbar, making it a Category 5 hurricane on the Saffir-Simpson hurricane scale, the 6th strongest Atlantic hurricane on record, and 3rd strongest to make landfall in the United States. By the time it made final landfall on the Gulf Coast on the 29th it had reduced in intensity to a central pressure of 928 mbar with winds at 194 kmh (121 mph), making it a mid-grade Category 3 hurricane [20].

But it was not high winds which led to the massive devastation; rather it was the extensive and high-intensity storm surge and the secondary flooding it caused. As the storm moved out of the Everglades and into the Gulf on the 26th, it rapidly became a very broad storm, a characteristic it maintained well into the Mississippi valley. At its final landfall, the storm's maximum winds extended an estimated 55 km (30 nm) from the eye, while hurricane force winds extended a minimum of 139 km (75 nm) outward. This broad size and its strong intensity over the Gulf generated a storm surge that was both broad as well as comparitively deep, in addition to significant waves built on top of this surge. The maximum storm surge measured was 8.74 m (27.8 ft) at Pass Christian, MS, with 6 m (20 ft) through most of Hancock County, MS, and up to 5.8 m (19 ft) in New Orleans itself. On top of this storm surge was the generated wave action, for which a National Data Buoy Center (NDBC) buoy south of Dauphin Island measured a maximum wave height of 16.8

m (55 ft) above MSL; this is also the highest storm wave ever reported by a NDBC buoy [20].

It was primarily this surge and wave action which flooded 80% of New Orleans, overtopped and later breached levees, flattened neighborhoods, turned streets into lumberyards, caused over $80 billion (USD) in damages, and led to the deaths of over 1,800 people.

1.2 Research Questions

Thus we are presented with MAVs seeing their first operational use in emergency response and recovery operations in a very wide area disaster. From this situation, this work endeavours to answer two central research questions.

• *What technical capabilities are required to use a MAV platform in this environment?*

How does a VTOL MAV handle urban flight conditions vs. free space flight? How are aerodynamics, control, telemetry, and other systems affected by flight in and around buildings? Are there any features that would make these operations easier on the pilot and flight team? Are there any of the canonical MAV features which do not perform well, or are not needed in this environment?

• *What is the most effective path to evolve MAVs from semi-autonomous to fully autonomous?*

How should features be ranked in terms of difficulty and necessity? Is an inspection type task even amenable to a fully autonomous platform? If not, what activities should be left as human-in-the-loop tasks and which could be automated to make the operations easier and more effective?

1.3 Contribution

This work makes two key contributions to the research community. The first of these is a historical record of the flights and operations to which future researchers can refer. By documenting each flight, this thesis can serve as a definitive record on the first use of MAVs in an urban emergency response situation. The second, and more important contribution however is to the field robotics community. This document describes the features needed for semi-autonomous MAV operations in cluttered urban environments, and by doing so can help guide future research with VTOL MAVs.

1.4 Thesis Organization

The remainder of this document is organized as follows. Chapter 2 discusses previous research on MAV flight operations in urban environments in the context of disaster response operations. Chapter 3 presents an initial task analysis covering the different types of emergency response scenarios and the different implications and requirements for MAVs while Chapter 4 discusses the methodologies employed in collecting and analysing the data. Following that, Chapter 5 describes the equipment employed as well as how the flight team was organized while performing the operations and Chapter 6 provides a record of each of the individual flights themselves. Finally, Chapter 7 synthesizes this information to draw several conclusions about the needed features and the path forward in evolving urban MAVs from semi-autonomous to fully autonomous platforms.

Chapter 2

Related Work

To properly contextualize this work, it is necessary to review work from two primary subject areas; Search and Rescue (SAR) robotics and VTOL MAV autonomy and urban flight operations.

2.1 SAR Robotics

The use of robots of any description during SAR operations is still a relatively new field, but there is some precedent with the use of Unmanned Ground Vehicles (UGVs) during field exercises as well as mass casualty incident responses. The first use of UGVs during an actual response was at the World Trade Center (WTC) terrorist attack in New York City. Micire discusses the different robot drops at the disaster site, how and where the robots were used (and not used), as well as how the robots failed and what needs to be done to correct these failures [24]. He proposes seven key areas that should be addressed for future Urban Search And Rescue (USAR) UGV work, namely: stovepipe system development (as exemplified by incompatible image processing systems), lack of automated tether management, weak wireless communications systems, self-configuration capabilities for polymorphic robots, Simultaneous Localization and Mapping (SLAM) capabilities for the UGVs, and finally, assisted navigation for the UGVs to facilitate operator mobility when inside the pile. Blackburn, Everett, and Laird also discuss the robotic response to the WTC disaster by the Navy's Space and Naval Warfare (SPAWAR) Systems Command in San Diego [2]. Both the SPAWAR team and the USF team (where Micire was a member) were coordinated under the direction of CRASAR while at WTC. While all site teams were placed under CRASAR direction while on site they operated essentially independently and saw different situations when operating. The SPAWAR report identifies cognitive tunneling, situational awareness, mobility limitations of the UGVs, and high cognitive load for the operator (partially induced by lack of semi-autonomous support capabilities on the UGVs as limiting factors during the deployment [2].

After this first robotic SAR deployment, robot teams have participated in several disaster response exercises to further understand how they can best be used in these situations. Gage et al. describe the experiences of a robot team which participated in the ShadowBowl 2003 exercise in San Diego. There is some discussion of the actual on-site robot drops, but the primary focus of this work was in testing out robotic reachback[1] methodologies and strategies [9].

Assembling observations from several of these responses, Murphy gives a thorough description of current FEMA Task Force (TF) command structure and disaster response protocol and how UGVs would need to be integrated into both of these [25]. She goes on to propose a domain theory for robot operation and the structure for information flow through the TF and Incident Command hierarchy [25].

2.2 VTOL UAV Urban Operations

The third subject area, urban MAV flight operations and MAV autonomy devolopment, has several notable sources as well. One important work dealing with urban MAV operations is the Blackhawk project described by Green and Oh [12]. This project 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

[1] Gage defines reachback as follows, 'Reachback refers to establishing communication between the first-responders at the scene of the disaster and other experts that may be geographically distant[9].'

rotary-wing vehicle for inspection tasks. One 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 ($T > W$ and $T/W > 1$), which further limits the already stringent payload restrictions on the aircraft. To determine the usefulness of such a vehicle for a USAR task it is important to decide if the gains in loiter time and transition speed outweigh the payload and stability limitations of such a hybrid.

Moving to traditional VTOL UAVs, Shim et al. demonstrated successful autonomous VTOL navigation between simulated urban obstacles [39]. 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, 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 [16]. 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 promising work in urban operations and obstacle avoidance is a paper by Scherer et al. from the Robotics Institute at CMU [36]. 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.

The fourth, but all together missing, subject area is the use of MAVs during disaster response and USAR scenarios. The author presented a preliminary version of this work during AUVSI 2006, but there are no other sources describing the use of MAVs in a disaster [30]. As the Katrina flights were the first use of MAVs for emergency response, this is the first series of works describing this type of use.

Chapter 3

Initial Task Analysis

To effectively conduct structural survey missions and, more importantly, be able to analyze the platform requirements for such a task, it is important 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.

3.1 Work Domains

Within the field of emergency management there are four standard phases in a disaster: the two pre-event phases, mitigation and preparedness, and the two post-event phases, response and recovery [27]. These two post-disaster phases deliniate the work domains where MAVs would be used for structural survey during emergency management.

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 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 (even when this is desirable during the response phase the reality of limited network availability and reliability make this difficult).

3.2 Required Output

In either work domain, structural inspection will need to provide the following 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. All of these shots must be high-resolution stills to provide enough information to structural experts (this initial hypothesis was later directly confirmed by the structural experts during reachback). Video can be useful, but only as a way to establish the overall scene, not to evaluate individual structural elements.

3.3 Airspace Opportunities

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. 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 perfectly suited for MAV operations. In particular, rotary-wing MAVs operating in this space can provide all of the data types presented in the initial task analysis.

3.4 Airspace Problems

For UAVs to fly in this zone between ground assets and manned aircraft, or indeed *anywhere* in the US National Airspace System (NAS), will require regulatory action by the Federal Aviation Administration (FAA). According to AC 91-57 and the February 6th, 2007 clarification to 91-57 "Unmanned Aircraft Operations in the National Airspace System" by Nicholas Sabatini, UAVs are not permitted to operate in the NAS for commercial or research purposes, except when authorized by a Certificate of Authorization (COA); and thus far COAs have only been issued to DoD and DHS [41, 35]. Noting that this issue most certainly exists, discussion and potential solutions to the issue are left for other writings.

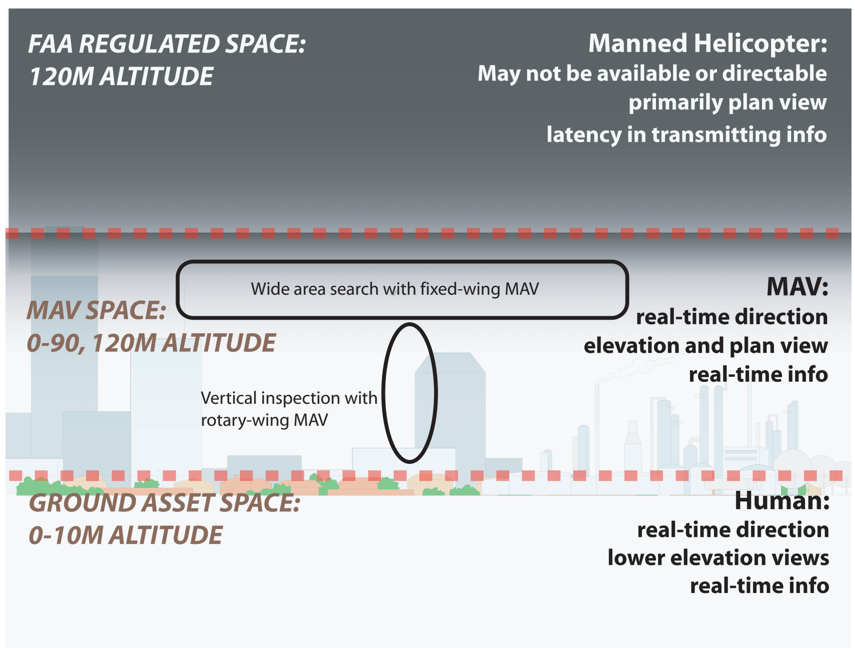


Figure 1: Vertical profile of an urban structural inspection task overlayed with asset operation zones. Rotary-wing MAVs provide increased capabilities over ground-based assets, and provide these capabilities at a lower cost and with a shorter sensor-analyst path than manned rotary-wing aircraft.

Chapter 4

Approach

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.

Figure 2: Map of Biloxi, MS showing locations of structures surveyed by the CRASAR team between November 26th - December 5th, 2005. Map © Google, 2006.

During each mission (which included all consecutive flights at one location) several pieces of data were collected. These included pre-flight and post-flight meteorological data sets, flight team voice recordings, flight team debriefs, video streams from 4 video cam-

Table 1: Location 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

eras, 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 members' comments about flight conditions and vehicle actions.

Chapter 5

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, Inc., an Institute for Safety, Security, and Rescue Technology (ISSRT) NSF Industry Center member company. The IP3 is 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 (10S3P) Lithium-Polymer battery pack, a 1.35 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-man 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;

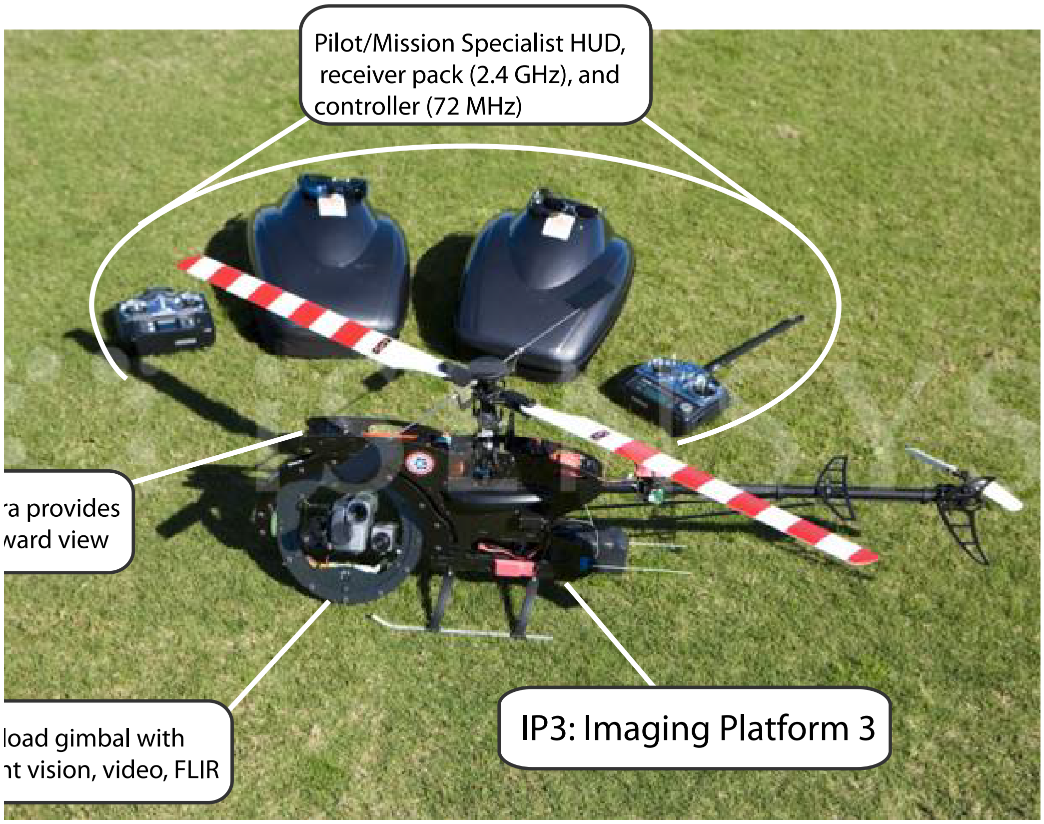
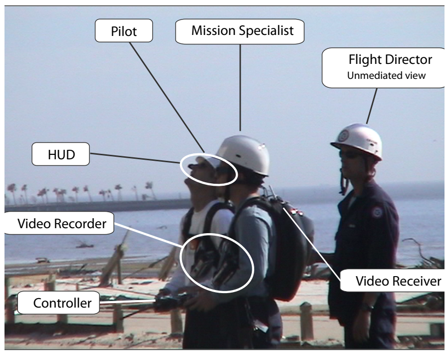


Figure 3: iSensys IP3 MAV plus Pilot and Mission Specialist operational equipment. Image © iSensys, Inc.

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.

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



(a) Flight Team with equipment

(b) Flight Team with mission responsibilities noted

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

Chapter 6

Flights

While conducting structural surveys during Hurricane Katrina recovery operations in Biloxi and Gulfport, MS, the CRASAR team conducted 32 flights at 7 sites over 8 days. While in and of themselves these are relatively innocuous operations, they carry some historical significance as Hurricane Katrina is the first disaster to see the use of any type of UAVs during either post-disaster phase. With that in mind, this chapter will detail each of these flight locations, the mission and surveillance objectives, and the conditions encountered at each site. These descriptions will then provide the basis for the conclusions drawn in Chapter 7. To begin this discussion, Table 2 provides a summary of the flights and lists each flight and provides the flight duration each.

6.1 Hancock County EOC

Even though it was not one of the multi-story commercial sites we were there to photograph, we flew the most number of flights at the Hancock County Emergency Operations Center (EOC). And while it was not a research target, these flights were just as important, as they gave us an opportunity to evaluate and test our teamwork processes, optics and video systems, and our control methods. Figure 5 shows an overview of the EOC taken during one of our test flights.

Table 2: Location, date, duration, estimated average altitude, and estimated average stand-off distance of all flights. Average flight time is 3:29 and median flight time is 3:15. †Data unavailable.

Date	Flight Location	Flight Number	Duration (m:sec)	Estimated Average Altitude (m)	Estimated Average Standoff (m)
11/29/05	Hancock EOC	1	†	15	†
		2	†	25	†
	Casino Magic	1	2:32	80	100
		2	4:15	60	30
		3	3:44	30	15
11/30/05	Grand Casino	1	2:28	120	40
		2	2:42	100	70
		3	0:34	20	25
	Hard Rock	1	6:46	50	30
		2	1:53	2	2
		3	1:04	25	10
		4	3:16	20	5
		5	3:07	50	15
12/1/05	Isle of Capri	1	4:55	40	60
		2	2:48	50	70
	President Barge	1	3:40	30	20
		2	2:05	20	5
		3	2:31	10	5
		4	3:28	15	2
12/2/05	Casino Magic	1	3:15	30	15
		2	3:45	20	10
		3	3:20	40	20
	Hard Rock	1	9:32	30	15
		2	2:27	40	20
	1550 Beach Blvd.	1	5:24	15	4
		2	6:28	20	8
		3	1:06	5	2
12/3/05	Hancock EOC	1	†	30	†
	President Barge	1	0:59	25	10
		2	5:06	25	5
		3	0:57	10	3
	1550 Beach Blvd.	1	7:00	15	4

Figure 5: Picture of the EOC in Hancock County, MS. This was taken during our third test flight at the site.

6.2 Casino Magic

As Table 1 notes, we conducted two missions at Casino Magic; the first operation once we were in Biloxi on November 29th and again on December 2nd. The target for the first mission was a partially damaged parking garage at the edge of the Casino Magic property. The lower floors of the garage were filled with debris and assorted flotsam that had accumulated when the storm surge had receded through the area. This made it difficult to see through the structure and tell if there was any damage to the interior vertical members or floor slab of the structure. Using the MAV we were immediately able to get a view point from above the structure and evaluate the deck structure. While we were flying during the recovery phase, Figure 6 below clearly shows this type of imagery could easily be used to quickly reconnoiter a structure and identify if anyone had sought refuge on the roof (particularly useful when the interior stability of the building can not be safely ascertained).

Figure 6: Northeast corner of the parking garage adjoining Casnio Magic. Part of a set of images we used to evaluate the integrity of the upper deck.

During the second mission at Casino Magic, we turned our attention to the barge mooring area. As with several barges in the area, the storm surge caused the Casino Magic barge to break its moorings and float free. Once free, the wave action on top of the storm surge turned the barge into a battering ram and caused severe damage to adjacent structures. In Figure 7 both the pilings the barge was originally moored to, as well as where it rammed the structural beams of the adjoining hotel are clearly visible. The pilings shown here are one clear example of the flight path obstacles that can be encountered during these operations (see Section 7.2 for more details).

Figure 7: Picture of the barge pilings at Casino Magic, and the damage to the hotel caused by the free-floating barge once broken loose by the storm surge.

6.3 Gulfport Grand Casino

Following this first mission at Casino Magic, our next mission was at the Gulfport Grand Casino. In contrast to the long, low parking garage before, the Grand Casino is a relatively tall building and only had visible damage on the seaward side (additionally, work crews were present on other sides of the building, so for safety concerns we limited ourselves to this side of the building). As noted in Section 7.5 below, one of the important findings from these flights was the importance of the pilot-view camera. Since Grand Casino was the tallest structure, and hence was the site of the highest flights, it provided an excellent opportunity to test this pilot-cam. When remotely piloting such a small MAV, it becomes easy to lose perspective and orientation on the vehicle when flying at any appreciable distance. Flying at 100 m nearly overhead, maintaining a mental model of the vehicle's orientation becomes a significant challenge. Section 7.5 provides further details, but these flights provided an excellent opportunity to utilize this pilot-cam and the perceptual augmentation it can provide. Figure 8 below shows one of the detail shots of damage being repaired on the south, sea-facing side of the Grand Casino, while Figure 9 is overhead pictometry survey data of the entire Grand Casino structure. This picture, and all the pictometry, was kindly provided by the Hancock County EOC team who had collected and organized all of this data.

Figure 8: Detail of partially repaired damage to the south facing side of the Grand Casino, which absorbed the brunt of the wind and storm surge damage.

6.4 Hard Rock Casino

Our next location was the Hard Rock Casino in Biloxi. Just as at several of the other casinos in the area, the gambling barges had come loose during the storm. Unlike the President,

Figure 9: Overhead pictometry of the Gulfport Grand Casino. The blue-roofed barge which is missing from in front of the Grand can be seen near the top of the frame. This was an unfortunately common occurance up and down the beach. Image is © Hancock County EOC, 2005 and is used with permission.

the Magic, and the Isle of Capri, for example, the Hard Rock's barges had stayed confined to their concrete mooring corral. However, instead of the two barges being moored side by side as they should be, they had ended up creating a two-layer lean-to against the landside hotel portion of the complex. Figure 10 shows one half of the two barges leaning against the building. During the flights at the Hard Rock Casino, one of the primary surveillance targets was to inspect what was above and behind these barges, as well as inspect the interface between the barges and the building, and how structurally stable that was. The second inspection target while flying at the Hard Rock was the lowest exterior guest room balcony, which had been partially collapsed by the movement of the barges. As Figure 11 shows, the damage was not particularly severe, but this type of damage (collapsed concrete slab with attached internal rebar reinforcement) provided an excellent opportunity to test the capability of the IP3 and the onboard optics to target and provide detailed imagery of focused damage.

For these surveys of the barges, the only available launching location was from the pier that had once encircled the barges. As the pier itself was only 2 m wide, it not only provided a limited landing area, but limited mobility to the flight team while operating. As with the dock launch at the Isle of Capri and the debris encountered around 1550 Beach Blvd., this limited launch location only served to reinforce the lessons learned regarding site access and restriction. Section 7.5 contains further information on the implications of limited site access.

In addition to the barges and the associated area, while at the Hard Rock we also flew at a secondary location. As Figure 20 shows, we used the IP3 to penetrate the damaged section of the hotel and inspect structural members from underneath. As is evident, this provided some very difficult flying for the pilot and underscored the need for an omni-directional obstacle avoidance system as described in Section 7.2.

6.5 Isle of Capri

The worst damage by free-floating barge battering rams occured at the Isle of Capri casino. At the Isle of Capri the barge had been moored between the hotel and the parking garage. Once the barge broke loose from its pilings the storm surge pushed it eastward into the parking garage, whereupon the wave action repeatedly drove the barge into the structure,

Figure 10: Picture of the eastern half of the two stacked barges leaning against the land-side building at the Hard Rock Casino. The white deck on the left is the first barge (with all superstructure removed by the storm), and the red deck is the 2^{nd} floor of the second barge. The rusted steel frame members are the south-facing wall of the building section.

ultimately causing the collapse of approximately one quarter of the parking garage. Figure 12 shows this multi-story hanging collapse on the parking garage.

In order to survey this damage to the parking garage we were required to launch from the yacht club dock behind the original mooring position. As detailed in Section 7.2, the pilings on this dock provided a very clear case for the need for obstacle avoidance technologies on a semi-autonomous MAV platform. Figure 13 below shows the dock with the launching location, as well as the dock's orientation to the parking garage to be surveyed.

The survey at the Isle of Capri also gave us an opportunity to test another modality of the inspection capability of the IP3. Though we were working during the recovery phase, and this technique would be more useful during the response phase, Figure 14 below shows

Figure 11: Detailed picture of damage to a guest room balcony. The second barge can be identified by the red patterned carpet in the lower left. This picture is approximately 50 m west of the image shown in Figure 10.

a very clear shot of the damage to the decking of the I-90 bridge eastbound out of Biloxi (Figure 12 shows the bridge in the background behind the garage). From the ground, we had no way to determine what condition the bridge was in, and were we operating as responders during the hours and days following Katrina we would have needed to make our way to the bridge, determine that it was impassible, and backtrack and come up with an alternate route. Even though the bridge was a short 2 km away from the dock, during the Katrina response progressing that far sometimes took the FEMA SAR teams hours as they picked their way through the trash and debris the receding storm surge had left in most of the streets and roads [40].

Figure 12: Collapsed portion of the Isle of Capri parking garage damaged by a loose barge. The I-90 bridge (Figure 14) is visible on the left side of the frame.

6.6 President Casino Barge

While many of the casino barges broke loose and landed elsewhere, the President Casino barge covered the most distance during the storm, ending up 1 km west and 100 m inland of its starting location. What finally stopped the barge from drifting any further was its collision with the roof of the Motel 6. As Figure 15 shows, once the water receded the barge was left high and dry next to the motel. During our flights around the President Casino barge we concentrated primarily on the three closest sides of the barge and the interface between the barge and the motel (seen in greater detail in Figure 21).

Each of the three sides we flew on the barge presented a unique flight condition and gave us an opportunity to learn something new. Beginning the discussion on the left side of the barge, ground access for the flight team is an important issue. We launched this flight

Figure 13: Yacht club dock used to launch the IP3 to survey damage at the Isle of Capri. The launch hazard presented by the support poles is clearly evident in this shot.

from the parking lot at the bottom of the frame, thus in order to get a good view of the entire length of the barge we had to fly at a somewhat extended range, limiting the pilot's perspective and perception of the helicopter. At one point, a radio glitch to the cyclic threw the helicopter out of a stable hover and into a left roll. As noted by the pilot immediately following, had we not had the pilot cam at that point, it would have been impossible to recover the helicopter. Figure 16 shows a comparison between the nominal view from the pilot cam and the image presented during the radio glitch.

Moving counter-clockwise around the barge, the lower side of the barge, where it is rammed against the motel, presented a very clear case for in-flight redirection and modification to the established flight plan. From the ground it is obviously impossible to tell the extent of damage at this seam; the majority of the roof could be caved in or there could

Figure 14: I-90 bridge heading east from Biloxi. As can be seen across the entire span, the combined storm surge and wave action lifted and then collapsed all of the deck segments of the bridge. This image was taken from the opposite side of the Capri parking garage and illustrates a valuable use case for MAVs conducting tactical reconnaissance for SAR units during the response phase.

be no damage at all, and until the helicopter can make an initial survey of this, it is not possible for the flight team to determine how much time needs to be spent surveying this damage. Figure 21 in Section 7.3 shows a detail shot of this joint.

Continuing around to the right side of the barge, this face presented the worst radio interference of all the flight locations. Through all the missions during the trip, radio interference was encountered at a greatly elevated rate compared to normal operations (an average of 1 to 2 hits per flight was encountered, whereas normal flight registers 1 to 2 hits per month of daily flying), but the steel beam construction, twisted superstructure, and mass of wires encountered on this south face of the barge presented even greater threat of reflected and multi-path interference. Figure 17 shows the south face of the barge with exposed metal superstructure and other interference hazards.

Figure 15: The President Casino barge where it came to rest approximately 1 km down the beach from its original mooring. The barge is the structure on the right of the frame topped by the red towers. The remaining buildings are part of Motel 6. Image is © Hancock County EOC, 2005 and is used with permission.

(a) Nominal pilot cam view

(b) Pilot cam view during a hard-banked nose dive caused by a radio glitch.

Figure 16: Images comparing nominal and aberrant pilot cam images from President Casino barge survey. At the time of the glitch the IP3 was at the edge of the pilot's perceptual range. As noted by the pilot during the mission debrief, without the pilot cam providing a horizon line, the glitch would have caused the loss of the craft.

Figure 17: South face of the President Casino barge showing exposed and mangled metal superstructure, steel beam construction, and hanging wires (primarily on first floor) which caused a high level of radio interference while flying near the barge. As with much field-work, and particularly emergency response operations, conditions are often very different from controlled testing, and most often for the worse.

6.7 1550 Beach Blvd.

The final location inspected was 1550 Beach Blvd., a two-building 4-story residential block. This was the only residential building inspected and as such, the only wood-frame (as opposed to steel frame) structure we inspected. The two buildings at the site were stacked in a roughly north-south orientation which consequently caused the southern building to act as a breakwater and absorb the majority of the wave action directed at the site. When we arrived, all that remained of the southern site was the concrete foundation, and the northern building was listing approximately 15 degrees to the north, reflecting the storm surge and wave action pressure. Figure 18 shows the overhead pictometry of 1550

Beach, with the concrete pad from the destroyed building visible near the top of the picture, the second building visible in the middle, and the accumulated flotsam and debris visible throughout the image, but particularly just below the second building.

This debris accumulation, as well as the damage to all sides of the building, illustrated in Figure 19, made this location a prime demonstration of the necessity to conduct operations as multiple short flights, rather than one long flight per site. While it is possible for the pilot to perform limited relocations while flying, the large quantities of debris encountered by the FEMA USAR teams made transitioning around the building impossible while in flight [40]. The optimum operational tempo evolved to be to take off and inspect one face, land, relocate, and launch to inspect the new building face.

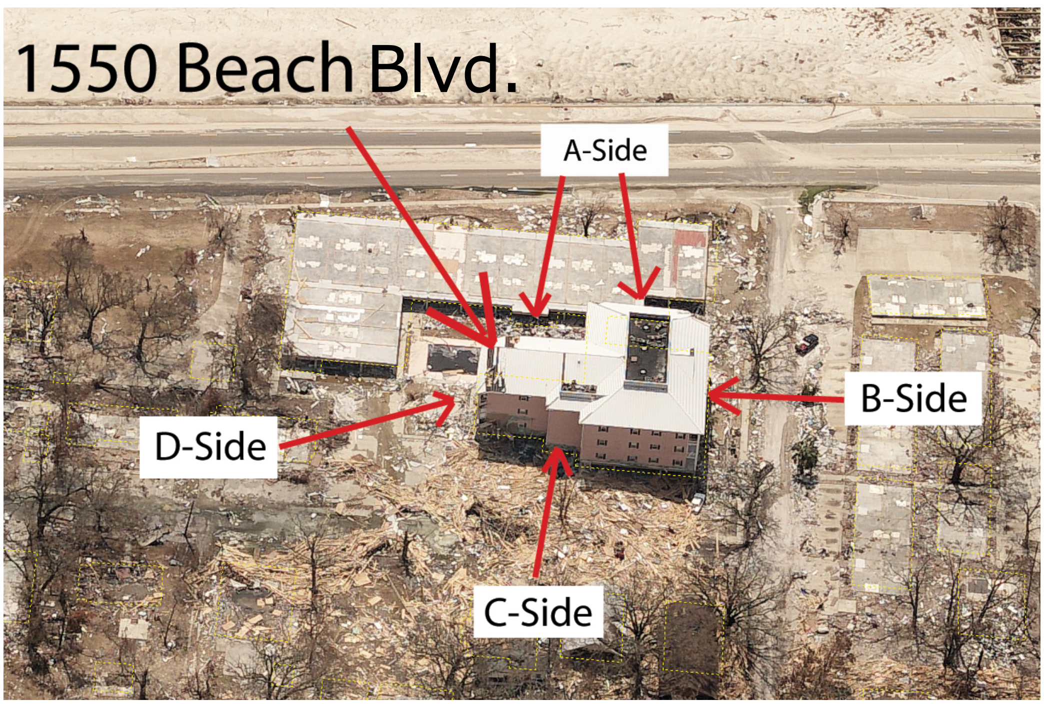


Figure 18: Pictometry of 1550 Beach Blvd. Shown the concrete foundation of the destroyed building (near the top), the remaining building in the middle, and the accumlated flotsam and debris just below it. Image is looking south, with the beach visible along the very top of the frame. Image is © Hancock County EOC, 2005 and is used with permission.

Figure 19: East face of 1550 Beach Blvd. showing collapsed second floor and damage to concrete/wood frame joint.

Chapter 7

Results

Originally we set out two central research questions to help structure the discussion, namely: What technical capabilities are required to use an MAV platform in this environment?, and What is the most effective path to evolve MAVs from semi-autonomous to fully autonomous? Reflecting on our flight operations in light of these two questions, we draw four central conclusions about conducting urban inspection-type tasks in cluttered urban environments. These operations show that a standoff range of 2-5 m 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-man flight team is required for each MAV.

7.1 Vehicle Standoff

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 a Canon EOS 5D camera body and a telephoto lens. The 5D shoots 12.8 megapixel images).

7.2 Obstacle Avoidance

For imaging purposes it was best to place the imaging targets in the lower half of the forward quadrant; this does not mean however, that that is from where all flight obstacles approached the vehicle. 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. It is easy to take pictures of targets that are 12 o'clock low, but as with many generations of fighter pilots, remember to watch your six.

Figure 20 shows the most complex environment 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.

Figure 20: The IP3 flying into a building to image concealed damage.

7.3 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 becomes rapidly not useful. Figure 21 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.

Figure 21: 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.

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, not seated at computer terminals.

7.4 Operator:Vehicle Ratio

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, a three-man flight team was used: Pilot, Mission Specialist, and Flight Director. As Figure 22 illustrates, the primary reason these roles cannot be combined without a severe degradation of performance is the lack of informational overlap between the three positions. While all team members are looking at the same scene, each member sees something different. In relation to the robot, the Mission Specialist has a purely egocentric view point, the Flight Director has a strictly exocentric view, and the Pilot alternates between exocentric and egocentric (though altogether different egocentric and exocentric views than the other crew members).

7.5 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; not only must the flight director be aware of all people in the flight area, but during

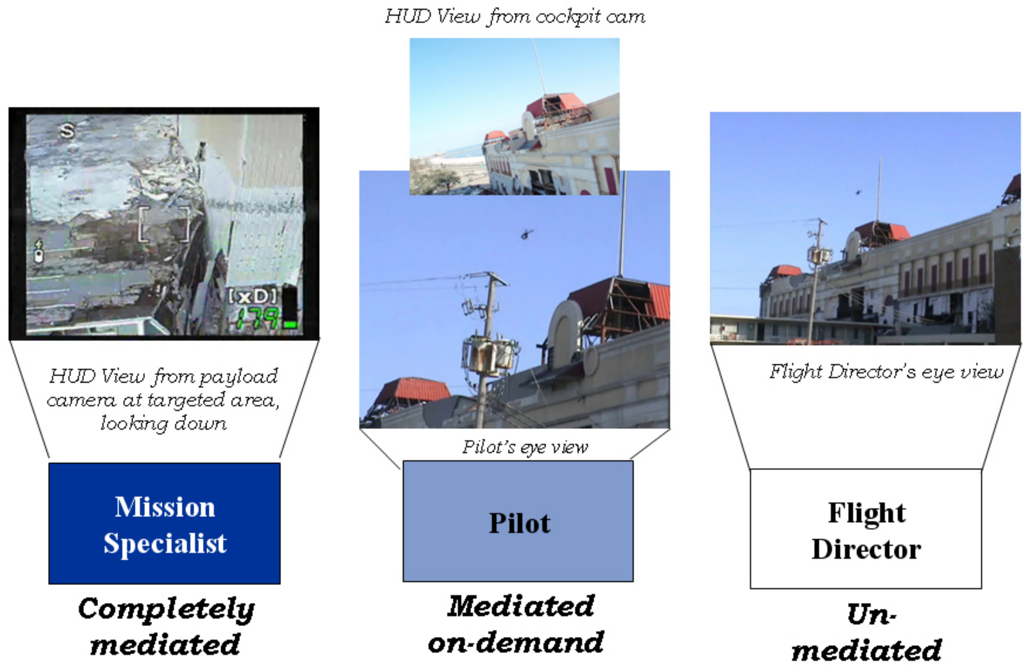


Figure 22: The three different views of the flight-team members. Each team member has a different focus and a different degree of computer mediation, making role combination difficult and undesirable.

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. Any professional-grade MAV system designed to operate in urban environments must take this into account.

One lesson that was fortunately only a confirmation of our initial design was the success of the pilot cam system. As illustrated in Figure 16 above, the pilot cam system provided a very simple but effective way of augmenting the pilot's active state information about the MAV while it was in the air. At both the Gulfport Grand Casino and the President Casino barge the pilot cam temporarily became the primary flight sensor, allowing the pilot to maintain control of the craft instead of recovering from a crash landing and the loss of the aircraft. At the Grand Casino the height of the target surveyed required the IP3 operate at the edge of the pilot's range, putting the pilot cam into an active support role to maintain a stable hover. At the President Casino barge, the MAV encountered a severe radio glitch to the cyclic, causing a hard, nose-down roll. In this case the pilot cam was the only sensor capable of providing the pilot sufficient information to recover from the glitch.

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, good landing zones and team positions were both difficult to come by, and those that were available were often far away and/or suboptimal. In short, compared to a typical hobby RC flight these flights were launched and recovered from smaller, more confined landing zones and conducted at longer standoff ranges. To address this problem, solutions that can extend the pilot's effective operating range and provide increased control of the MAV are needed. Figure 18 in Section 6.7 above shows the debris that accumulated around 1550 Beach Blvd.

7.6 Proposed Vehicle Feature List

Having noted these four central conclusions from the flights, it is possible to step back and synthesize these results and other observations and propose a feature list for future vehicles. Thus we have the following reference design for a VTOL MAV for an example urban inspection application, such as emergency response USAR. Such an MAV should be electrically powered and man-packable and it should have a pilot cam, stabilized hover, both manual and semi-autonomous flight modes, video and high-resolution still payload output, obstacle avoidance, upgraded radio links, payload stabilization, payload 'return-to-center',and a hands-off hover/'hover here' capability. Table 3 lists each of these features and the origin of this recommendation.

Table 3: Feature list for USAR MAV reference design.

MAV Feature	Source
Electric	Ease of transportability Field recharge capability
Man-packable	Mobility Standard FEMA equipment sizing Interview with FEMA USAR specialist[40]
Pilot cam	Pilot outbrief 11/30 Grand Casino Flight 1 12/1 President Barge Flight 2
Stabilized hover	Pilot outbrief 11/30 Grand Casino Flight 1 12/2 Hard Rock Flight 1
Dual flight modes	Post-deployment synthesis
Video and hi-res stills	Interview with FEMA USAR specialist[40]
Obstacle avoidance	Pilot outbrief 11/30 Hard Rock Flight 2 12/1 President Barge Flight 4 12/2 1550 Beach Blvd Flights 1, 3 12/3 President Barge Flight 3
Upgraded radio	Pilot outbrief 11/30 Hard Rock Flight 2 12/1 President Barge Flights 1-4
Payload stabilization	Mission Specialist outbrief 11/30 Hard Rock Flight 1 12/2 Casino Magic Flight 1
Payload ‘return-to-center’	Mission Specialist outbrief 11/30 Hard Rock Flight 1
‘Hover here’	Pilot outbrief 11/30 Grand Casino Flight 1 12/2 1550 Beach Blvd. Flight 2 Post-deployment synthesis

Chapter 8

Conclusion

The conclusion to this work breaks down into two components, Section 8.1 which sumarizes the results discussed thus far, and Section 8.2 which lays out a development path for vehicle autonomy in VTOL MAVs.

8.1 Summary

When it assaulted the Gulf Coast in the late summer of 2005, Hurricane Katrina instantaneously became one of the most disastrous hurricanes in recent memory; a hurricane whose effects will continue to be felt in the Gulf Coast region for years, and likely decades, to come. In addition to this tragic devastation, Hurricane Katrina is of historical import for another reason, namely, the response and recovery phases of Hurricane Katrina saw the first operational usage of UAVs during a disaster response. CRASAR deployed teams equipped with VTOL MAVs twice to the disaster area; once immediately following the hurricane during the response phase, and again 90 days later during the recovery phase.

As these are the first operational deployments of MAVs, there are many questions they can help answer, but the three core research questions are as follows: What team processes are necessary to fly an MAV in a cluttered urban environment?, What technical capabilities are required to use an MAV platform in this environment?, and What is the most effective path to evolve MAVs from semi-autonomous to fully autonomous? Using these questions as a starting point, video logs and crew debriefings were analyzed to arrive at the following four central conclusions. First, with basic COTS optics the minimum necessary standoff range for a VTOL MAV in a structural inspection task is 2-5 m. Second, while it is most intuitive to image targets straight ahead at a down elevation, obstacles can and will encroach on the vehicle's airspace from all angles; an MAV in urban environments needs omni-directional obstacle avoidance to successfully move to higher levels of autonomy. Third, given the operational tempo and the highly dynamic nature of the flights, it does not appear that GPS waypoint navigation would be a useful feature for urban inspection type operations. And finally, safety and informational context concerns dictate that for the time being these operations take three operators to run one MAV in the field.

8.2 Future Work

So what of the way forward then? The most pressing research areas for future work are in incremental autonomy and a better understanding of the human-factors and interface issues. This includes areas such as platform stabilization, payload stabilization and visual servoing, complete spherical obstacle avoidance, augmented reality pilot displays, multimodal interfaces, and team performance metrics.

With such a list however it is important to provide a more formalized and directed version, something which can direct and guide future research in VTOL MAV autonomy. Figure 23 illustrates the proposed development plan.

The upper left corner of Figure 23 shows that the operations conducted following Hurricane Katrina were entirely teleoperated. The next step from direct teleoperation (pilot commands as actuator inputs), is attitude stabilization or a fly-by-wire design (pilot inputs as requested 6-DOF attitude modifications). In the time since Katrina, some platforms have reached this attitude stabilization capability, with most current platforms operating somewhere along the continuum between these states. The next step past stabilization is obstacle avoidance and a guarded motion behavior, wherein the pilot requested attitude adjustments are now filtered with an obstacle avoidance behavior to prevent collisions. The

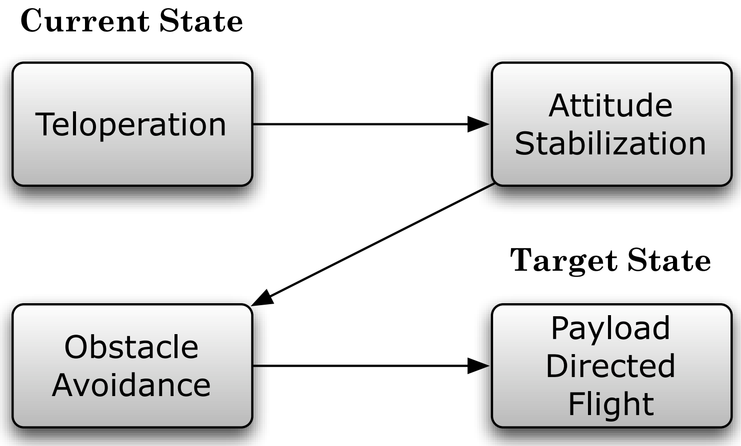


Figure 23: Development path for the implementation of autonomy in VTOL MAVs for urban inspection applications.

final target state for autonomy development in VTOL MAVs should be payload directed flight. Field operators of such a platform, such as USAR operators, are only interested in the payload data output, not how the vehicle stays in the air. Thus, if the pilot or operator can simply direct the payload camera towards their intended target, and the helicopter uses its stabilized hover and obstacle avoidance behaviors to follow the payload as the operator flys the camera, operation and required training for such a platform would both be greatly simplified.

Although Figure 23 presents this as a linear progression, the two layer breakdown is not entirely accidental. The first two control methodologies can also be thought of as simply teleoperation and advanced teleoperation; the attitude stabilization offloads some of the inner loop control requirements from the pilot, but it does not make any control inputs to drive the aircraft to any particular location. Dropping down to layer two and obstacle avoidance however the autonomy begins to aid the pilot in moving, or more often *not* moving, the aircraft through the environment. With the final step of payload directed flight, the automation becomes responsible for all of the drive inputs, responding only to qualitative pilot commands such as ‘up and to the left’. With this progression up through the layers of the path planning system, there is little option for this progression to happen in any other manner.

As a final point, it is important to compare this proposed development path with what appears to be the more traditional GPS-based development path. Fortunately this difference appears to based on one core difference between the methodologies: frame of reference. The above proposed development path orients the control and autonomy problems to the pilot’s frame of reference, while traditional GPS systems are derived from a world based absolute coordinate system; it is a question of human-centered design compared to a world referenced methodology. In the target state of the propsed system a pilot designates a target by simply pointing the camera at it, whereas designating a target in a GPS system often requires entering a lat. long. coordinate pair for the target. While geo-referenced coordinate systems work well for larger UAVs operating on a global scale, smaller MAVs operating at a local and human scale are better served by operating within this coordinate system.

References

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

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

[3] G. Bland, P. Coronado, T. Miles, and J. P. Bretthauer. The AEROS project: Experiments with small electric powered uavs for earth science. In *Infotech @ Aerospace*, Arlington, VA, 26-29 September 2005.

[4] J. L. Burke. 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, September 2003.

[5] G. L. Calhoun and M. H. Draper. Multi-sensory interfaces for remotely operated vehicles. In N. J. Cooke, H. L. Pringle, H. K. Pederson, and O. Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7, pages 149–165. JAI, 2006.

[6] J. Casper. 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, May 2002.

[7] R. A. Chadwick, S. L. Pazuchanics, and D. J. Gillan. What the robot's camera tells the operator's brain. In N. J. Cooke, H. L. Pringle, H. K. Pederson, and O. Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7, pages 373–384. JAI, 2006.

[8] W. J. Clancey. *Observation of Work Practices in Natural Settings*, pages 127–145. Cambridge University Press, 2002.

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

[10] R. A. Garay. Marine corps systems command liaison team: Field report central iraq, 20 april to 25 april 2003. Field report, United States Marine Corps, 2003.

[11] S. Gourley. Raven uav. *Army Magazine*, 55, 2005.

[12] W. Green and P. Oh. Autonomous hovering of a fixed-wing micro air vehicle. In *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, pages 2164–2169, May 15-19, 2006.

[13] D. E. Grilley. Resolution requirements for passive sense and avoid. Technical report, Alion Science and Technology, 3592 Collins Ferry Rd. Ste. 180, Morgantown, WV, 26505, January 26 2005.

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

[15] S. B. Hottman and K. Sortland. Uav operators, other airspace users, and regulators: Critical components of an uninhabited system. In N. J. Cooke, H. L. Pringle, H. K. Pederson, and O. Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7, pages 71–88. JAI, 2006.

[16] S. Hrabar, G. Sukhatme, P. Corke, K. Usher, and J. Roberts. Combined optic-flow and stereo-based navigation of urban canyons for a uav. In *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on*, pages 3309–3316, 2-6 August 2005.

[17] B. P. Hunn. Video imagery's role in network centric, multiple unmanned aerial vehicles (uav) operations. In N. J. Cooke, H. L. Pringle, H. K. Pederson, and O. Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7, pages 179–192. JAI, 2006.

[18] B. P. Hunn and O. H. Heuckeroth. A shadow unmanned aerial vehicle (uav) improved performance research intergration tool (imprint) model supporting future combat systems. Technical Report ARL-TR-3731, Army Research Laboratory, February 2006.

[19] H. L. Jones, E. W. Frew, B. R. Woodley, and S. M. Rock. Human-robot interaction for field operation of an autonomous helicopter. In H. M. Choset, editor, *Mobile Robots XIII and Intelligent Transportation Systems*, volume 3525. SPIE, 1998.

[20] R. D. Knabb, J. R. Rhome, and D. P. Brown. Tropical cyclone report: Hurricane katrina: 23-30 august 2005. Technical report, National Hurricane Center, August 2006.

[21] J. S. McCarley and C. D. Wickens. Human factors implications of uavs in the national airspace. Technical Report AHFD-05-5/FAA-05-1, University of Illinois Institute of Aviation: Aviation Human Factors Division, Savoy, IL, 2005.

[22] T. McGeer and J. Vagners. 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, July 1999.

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

[24] M. Micire. 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, July 2002.

[25] R. R. Murphy. Human-robot interaction in rescue robotics. *Systems, Man and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, 34(2):138–153, May 2004.

[26] R. R. Murphy and J. L. Burke. 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*, September 2005.

[27] NGA. Comprehensive emergency management: A governors guide. Technical report, National Governors' Association, 1979.

[28] T. Oron-Gilad, J. Y. C. Chen, and P. A. Hancock. Remotely operated vehicles (rovs) from the top-down and from the bottom-up. In N. J. Cooke, H. L. Pringle, H. K. Pederson, and O. Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7, pages 37–47. JAI, 2006.

[29] H. K. Pederson, N. J. Cooke, H. L. Pringle, and O. Connor. Uav human factors: Operator perspectives. In N. J. Cooke, H. L. Pringle, H. K. Pederson, and O. Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7, pages 21–33. JAI, 2006.

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

[31] M. Quigley, B. Barber, S. Griffiths, and M. A. Goodrich. Towards real-world searching with fixed-wing mini-uavs. In *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ*, Edmonton, Alberta, Canada, August 2005.

[32] M. Quigley, M. A. Goodrich, and R. W. Beard. Semi-autonomous human-uav interfaces for fixed-wing mini-uavs. In *Intelligent Robots and Systems, 2004. (IROS 2004). 2004 IEEE/RSJ International Conference on*, Sendai, Japan, September 28 - October 2 2004.

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

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

[35] N. Sabatini. Unmanned aircraft operations in the national airspace system. FAA Notice, February 6 2007.

[36] S. Scherer, S. Singh, L. Chamberlain, and S. Saripalli. Flying fast and low among obstacles. In *Robotics and Automation, 2007. ICRA 2007. Proceedings 2007 IEEE International Conference on*, 2007.

[37] W. Schneider. Defense science board study on unmanned aerial vehicles and uninhabited combat aerial vehicles. Technical report, Office of the Under Secretary of Defence For Acquisition, Technology, and Logistics, February 2004.

[38] B. P. Self, W. R. Ercoline, W. A. Olson, and A. P. Tvaryanas. Spatial disorientation in uninhabited aerial vehicles. In N. J. Cooke, H. L. Pringle, H. K. Pederson, and O. Connor, editors, *Human Factors of Remotely Operated Vehicles*, volume 7, pages 133–146. JAI, 2006.

[39] D. H. Shim, H. Chung, H. J. Kim, and S. Sastry. 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.

[40] S. Stover. Personal Interview with Sam Stover, member IN-TF1, December 2005.

[41] R. J. V. Vuren. Advisory circular 91-57. FAA Notice, June 9 1981.

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

[43] R. E. Weibel and R. J. Hansman. Safety considerations for operation of unmanned aerial vehicles in the national airspace system. Technical Report ICAT-2005-1, MIT International Center for Air Transportation, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 02139, March 2005.

[44] J.-C. Zufferey and D. Floreano. Toward 30-gram autonomous indoor aircraft: Vision-based obstacle avoidance and altitude control. In *Robotics and Automation, 2005. ICRA 2005. Proceedings*, 2005.