Overview of Requirements for Semi-Autonomous Flight in Miniature UAVs

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ABSTRACT: An emerging research area in rotary-wing Miniature UAVs (MAVs)[1] is operations in confined urban environments. This paper identifies four considerations for incrementally developing autonomy. These conclusions are based on an 8-day deployment to Biloxi, MS teleoperating an iSensys IP3 MAV for a post-Hurricane Katrina survey of structural damage to seven multi-story commercial buildings. First, the aircraft must maintain a range of 3-10m from these structures for optimal viewing while simultaneously detecting and avoiding obstacles. Second, weather conditions, particularly variable and unpredictable wind turbulence, lead to instability and can cause unrequested movements on the order of several meters. Third, given these sudden movements, complete spherical proximity sensor coverage is necessary versus conventional lateral, forward, nose-down placement. Fourth, this work suggests that 'return to last known good communications point' and 'location hold' behaviors are the logical next steps in autonomy, while GPS waypoint navigation appears less of a priority given that flight paths were dynamically changed and targeting was opportunistic in nature. The paper also discusses effective teleoperation strategies and roles of human operators.

I. INTRODUCTION

Recently, tactical intelligence has emerged as a critical tool across several professional communities. From military operations in Baghdad to search and rescue in Biloxi, police in St. Louis to firefighters in the Sierra Nevada mountains, everybody wants to know what is around the next building, and over the next hill. Traditionally, there have been two primary ways to get this information: walk to the location and look or use a manned helicopter to observe the location from the air. The first is often difficult, dangerous, or impossible, and the second is time-consuming, expensive, and usually rare. Helicopter-based MAVs can provide this same data more effectively, and more rapidly than their full-size brethren. To perform these types of missions competently however, often requires the helicopter fly as close as three meters away from a given obstacle or set of obstacles (see Figure 1).

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[1] MAV—Miniature UAV. For the purposes of this paper, a MAV is defined as an unmanned aerial vehicle with a rotorspan or wingspan less than 2m.

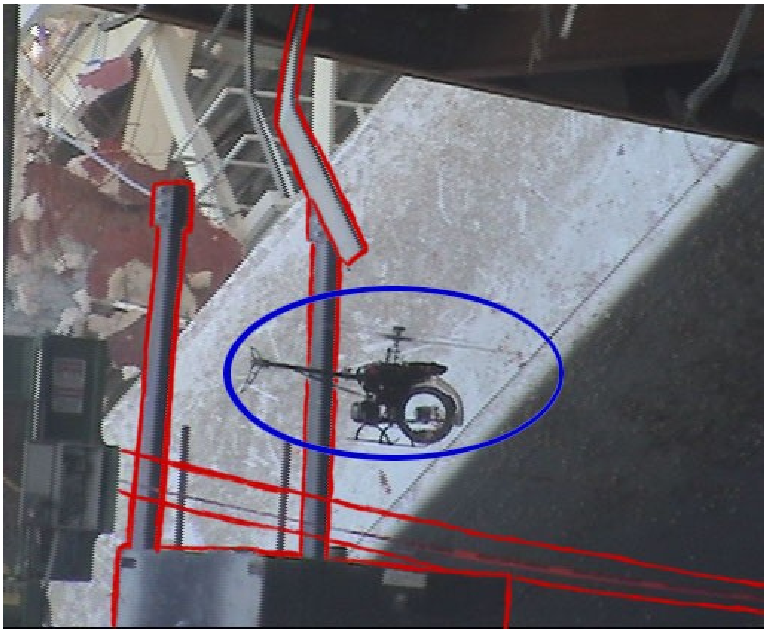

Figure 1: Flying into a damaged casino. IP3 outlined in blue, and obstacles noted in red. Obstacles (currently) within 3m of the helicopter include steel posts, red caution tape, and dangling ceiling supports.

But flying these missions is both difficult and exhausting, even for experienced pilots. To become a useful tool to the professionals who need this data, MAVs will need to become both safer and simpler to fly in this environment. One way to realize this change is to make the aircraft semi-autonomous; give the helicopter stabilization and obstacle-avoidance capabilities so the operator is not required to do this in addition to his other duties.

In order to successfully develop this technology, researchers will require an understanding of several key topics related to these types of missions. The first of these is operating conditions. What types of aerial obstacles are to be expected? How much physical access should be expected to flight areas? What non-obvious hazards need to be accounted for? Another area to be addressed is sensor coverage. What field of view does the MAV need to protect itself in a complex 3D environment? The third key area of understanding is weather conditions, the most important of which is wind. As the size of the platform shrinks, the wind's effects become greater and greater. When operating in cluttered environments, what wind conditions will the MAV need to deal with? The final topic is a discussion of features that would be important to any aircraft performing these missions.

Recently, a helicopter-based MAV developed by iSensys Corporation was used to survey damage from Hurricane Katrina to multi-story commercial structures in Biloxi and Gulfport, Mississippi. Data and observations from this survey work are used to provide answers to the above questions.

To that end, the remainder of the paper is arranged as follows. Section II: Approach gives an overview of how the Biloxi survey data was interpreted to answer the semi-autonomy questions proposed earlier. Section III: Equipment details the iSensys IP3 platform, and its use in the field. Section IV: Experiments describes the survey flights conducted in Biloxi. Section V: Results presents the responses to previously detailed questions. And finally, Section VI: Conclusions and Future Work summarizes the MAV operations as applied to semi-autonomy then specifies some of the next steps to be taken in this research.

II. APPROACH:

As mentioned, there are several applications and environments where semi-autonomous MAV helicopters would be a useful asset. One of these environments is a wide-scale disaster area as is present in Katrina's wake along the Gulf Coast region of Mississippi and Louisiana. While some operations may be in less constrained environments, the sites flown in Biloxi provide a reasonable worst-case scenario which any semi-autonomous platform should be able to handle with ease.

During the survey work, we flew seven different sites multiple times over a five day period. The variation in the sites and conditions provides a sufficient sample from which to initially refine the research questions, and then provide the needed answers. Both video and still imagery, combined with observations made by the entire research team were used as data for this investigation.

III. EQUIPMENT:

The primary vehicle for this research was the IP3 (Imaging Platform 3) designed and produced by iSensys (the IP3 itself is a highly modified Mikado LOGO 14). The helicopter itself had a rotorspan of 1.35m, a combined weight of 4.5kg, is powered by a lithium-polymer flight pack, and has a single charge flight time of 12-15 minutes. The heart of the modifications, however, was a 25cm camera gimbal mounted in the nose of the helicopter. The gimbal provided continuous rotation through all three primary orientation axes (pitch, yaw, and roll) and allowed the camera payload to be focused on any target within the helicopter's field of view. To operate the gimbal and camera, the flight team also had a mission specialist to command the payload. The primary product of this platform is video and still photo image data. To be able to view and direct the payload, the mission specialist had wireless video receiver (and matching transmitter on-board the aircraft), a pair of video goggles to view the data, and a standard R/C radio transmitter for directing the gimbal.

The pilot, in addition to the standard R/C controller, also had a similar video receiver/display goggles pair. In addition to the payload camera, the IP3 also provides a video view to the pilot from what would be a pilot's vantage point in a traditional helicopter (pointing straight forward from the nose of the helicopter). For images of the helicopter and all attendant support equipment, please refer to Figures: 2-4, which illustrate the IP3 and both the Pilot and Mission Specialist's equipment.

Figure 2: IP3 with support equipment

Figure 3: Kevin Pratt (Mission Specialist) with transmitter, video receiver, and eyepiece

Figure 4: Chandler Griffin (Pilot) with IP3

IV. EXPERIMENTS:

The experiments for this research consisted of five days worth of structural survey flights conducted at seven different multi-story commercial structures in Biloxi and Gulfport, MS. Six of these structures were waterfront casinos, which typically consisted of a multi-story building and an attached, permanently moored, gambling barge. The seventh structure we examined was a wood-framed beach-front condo unit. Please refer to Table 1 for the dates and locations of the flights.

Date	Location	Latitude	Longitude
11/30/2005	Grand Casino Gulfport	30° 21' 42”	89° 6' 6”
	Hard Rock Casino	30° 23' 28.6”	88° 53' 13.6”
12/1/2005	Isle of Capri	30° 23' 21.8”	88° 51' 36.4”
	President Casino	30° 23' 29.2”	88° 58' 36.4”
12/2/2005	Casino Magic	30° 23' 29.4”	88° 51' 46.8”
	Hard Rock Casino	30° 23' 28.6”	88° 53' 13.6”
	1550 Beach	30° 23' 38”	88° 55' 49”
12/3/2005	President Casino	30° 23' 29.2”	88° 58' 36.4”
	1550 Beach	30° 23' 38”	88° 55' 49”

Table 1: Flight Dates and Locations

V. RESULTS:

As mentioned, the findings from this trip can be fit into 4 primary categories: operating conditions, sensor coverage, wind conditions, and a discussion of features. These topics will be addressed in this order.

OPERATING CONDITIONS: OBSTACLES

This topic is composed of three questions. 1) While operating a MAV in a complex three-dimensional environment, what obstacles, and types of obstacles might be encountered? 2) What kind of physical access (on the ground) can be expected to flight areas? And 3) are there any non-obvious threats posed by this environment? For explanation purposes, we will use Search and Rescue (SAR) as an example application of a semi-autonomous helicopter.

During SAR, and particularly USAR (Urban Search And Rescue), a MAV could easily be used in both urban and suburban areas, and should be able to handle obstacles from both domains, including: phone poles, flag poles, power lines, building faces (from all angles), awnings/overhangs, and trees.

That being said, these are the same obstacles one would encounter flying outside any research lab. USAR operations commonly occur in disaster areas near collapsed or compromised buildings, particularly in a wide area disaster such as Hurricane Katrina. Figures 5-7 show examples of some of the obstacles encountered during our research.

Figure 5: Rooftop flagpole on the President Casino barge (taken from cockpit/pilot view video camera)

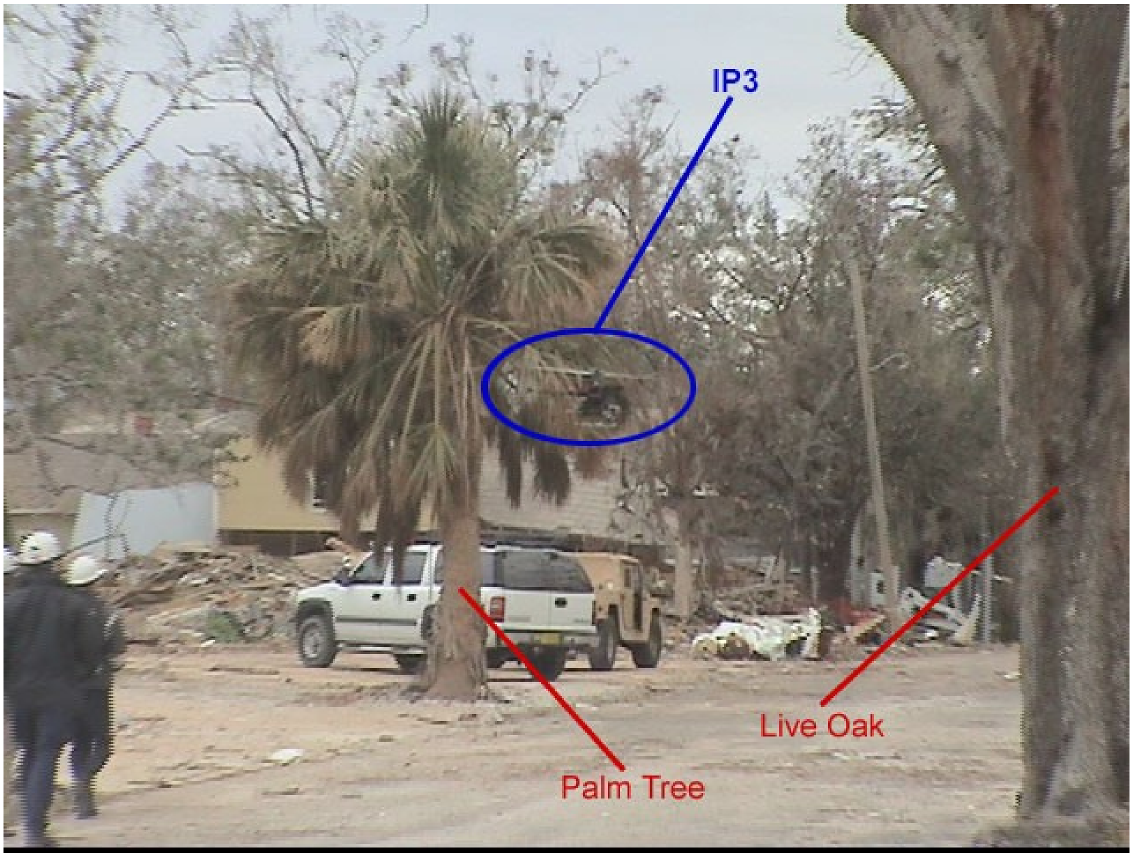

Figure 6: IP3 flying under trees. Here the helicopter is being transitioned from one building face to another. Just out of frame is the canopy of the live oak, which was a large navigation hazard

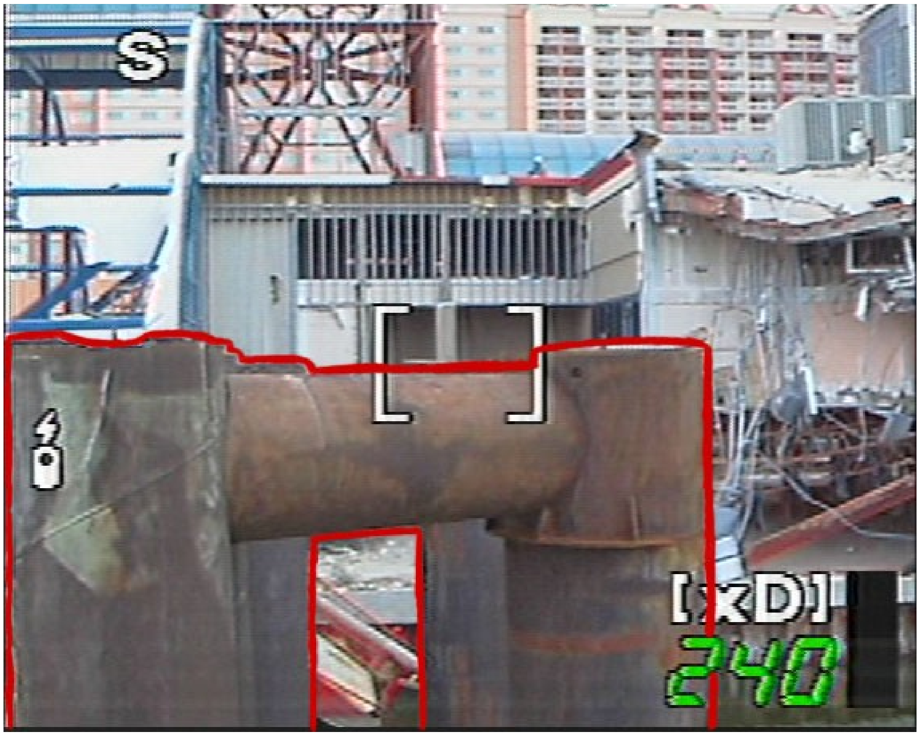

Figure 7: Barge Moorings from Casino Magic (taken from payload camera). Moorings are outlined in red.

In compromised structures however, things are going to be wildly out of place, and this presents another, more unpredictable, hazard not likely to be encountered in the lab. Figure 1 provides an example of this. In this picture, the helicopter had penetrated 3-4m into the first floor of the building to get a better view of a damaged structural beam. Within 3m of the helicopter, several obstacles are visible. Two vertical steel beams are highlighted in the middle left of the image, running across the bottom of the picture is red caution tape blocking off the area, and dangling from the ceiling is a light colored ceiling support which used to hold the ceiling tiles up. Of the obstacles we encountered, this type of obstacle is more dangerous than most. Not only is it not supposed to be there (making it easier for a pilot to miss it when reviewing the flight area), but it may begin moving in a light breeze.

With a representation of obstacles in mind, it is worth making a few observations about the helicopter flight. Even though the helicopter is capable of over 130 kph (37 m/s) standard operating speeds were typically 2 m/s (7.2 kph) or less. Observation and intelligence gathering needs a stable platform, so to be a useful tool, obstacle avoidance behaviors need only be capable of that operational speed.

It is also interesting to note something of the hover characteristics of helicopters of this size. When in a hover, even professional pilots can be expected to move up to 1 rotorspan in any direction. In our case this meant the helicopter could move a meter in any direction, even while hovering.

OPERATING CONDITIONS: SITE ACCESS

As stated in the obstacle discussion, operating conditions outside the lab and in a disaster area often vary wildly. This also applies to physical access to flight areas during an operation. While in Biloxi we spoke with the Biloxi Fire Chief and one of the FEMA USAR specialists that had searched the Biloxi area during the first ten days after the storm. One of the biggest problems they encountered was lack of access. Most days they were forced to leave their trucks at the Emergency Operations Center, and work solely on foot. And even while on foot, there were some areas that they had trouble getting to. All the destroyed buildings had to end up somewhere, and that was typically in large trash drifts in the middle of the street. In short the pilot of any semi-autonomous MAV used in a real mission cannot be guaranteed a large cleared flat area to launch and recover from. In fact, the pilot can almost be guaranteed that they will not be able to fly from where is most comfortable. This would likely mean a cramped launch pad, or a large stand-off distance (see Figure 8 for a picture of a launch from a cluttered pool deck).

Figure 8: IP3 Launching from a cluttered pool deck. In a disaster area, physical access is often not ideal.

Consequently, anything that can be done to increase the functional stand-off range of the platform is important. Two simple examples of this are stronger radios (something we plan to use in the future) and the pilot-eye camera mounted on the helicopter (as deployed during this expedition). As an anecdotal example, during one flight, the helicopter was nearly 200m away (nearing the limit of the radio controllers) when it suffered a strong radio glitch in the cyclic control. Fortunately, the pilot was able to use the horizon line provided by the pilot camera to adjust the roll and return it to a safer range. Per his own words, without the camera, he would have lost the helicopter.

OPERATING CONDITIONS: NON-OBVIOUS HAZARDS

Which brings up the third segment of operational conditions, non-obvious hazards. The biggest factor in this category is radio interference, or glitches. Our pilot, a professional R/C pilot, said that glitches are a known problem in the R/C world, but were usually rare. We had a minimum of one glitch each day, and usually closer to three or four —well past what the rate should be. Figure 9 provides a clear example of one reason why these were so common; large quantities of twisted metal. All the barges were steel-frame construction, and had steel wall studs, and steel siding. After being mangled by the hurricane this mass of metal led to multi-path signal problems.

As with the physical access problem, one straightforward solution to this problem is stronger radios—though this will just move the problem area further from the pilot. A more sophisticated solution would be some form of input monitoring or control dampening on the aircraft to prevent sudden radical deflections of the control surfaces. The IP3 is capable of aerobatic flight, but as a camera platform, it certainly has no need for that type of flight, or control response.

Figure 9: IP3 Hovering in front of a destroyed barge. Radio glitches were a common problem, and a major factor in these was twisted and scattered metal causing multi-path signal interference. Following Figure 1, this provides another example of disaster area obstacles (hanging wires and sheet metal)

SENSOR COVERAGE

With that understanding of operational conditions, we proceed to the topic of sensor coverage. In the obstacle discussion, we covered obstacles from all angles. Caution tape or a railing could come at the helicopter from below, a column or wall can approach level with the helicopter from any direction, and wires, hanging debris, or an overhang can threaten the helicopter from above. This array of threats, coupled with fact that by its nature, a helicopter can, and during any given flight can be reasonably expected to, move in all 6 directions available to it. This leaves only one logical conclusion. Anything less than complete spherical obstacle avoidance sensor coverage is insufficient. Any area left uncovered means the pilot is still responsible for obstacle avoidance in that quadrant, and consequently is still bearing the cognitive load for this task.

WIND CONDITIONS

During each flight, we collected a standard set of meteorological data, the most important of which was the wind conditions. This data was collected at 1.5m and again at 6m AGL, between 3 and 10m away from the take-off point. Table 2 presents the meteorological data collected. We also had the pilot make observations about the wind conditions (these proved more useful than the sampled wind data). And while this sampled data is useful, it should be noted that the pilots observation appeared to have a low correlation to this data; wind conditions often changed abruptly and unpredictably when near structures.

Location	Date	Height	Wind Max (kts)	Wind Avg (kts)	Rel. Hum. (%)	Press. (MB)	Avg Temp (C°)	Wind Chill (C°)	Dew Pt (C°)
Grand Casino Gulfport	11/30/2005	1.5m	5.7	4.2	49.7	1020	***	***	***
		7m	8.4	4.2	51.4	10.2	16.6	***	16.7
Hard Rock Casino		1.5m		3.5	58.6	1018	17.3	***	13.5
		7m	8.2	4.2	***	***	***	***	***
Isle of Capri	12/1/2005	1.5m	***	3.8	30.9	1018	22.8	23	5.4
		7m	7.5	2.2	32.2	1017	22.7	22.1	4.6
President Casino		1.5m	4.2	1	50.9	1016	23.9	24.1	17
		7m	5.1	0.8	100	1016	17.8	17.8	16.8
Casino Magic	12/2/2005	1.5m	14	2.8	39.3	1023	11.2	11.4	-1.3
		7m	14	2.7	36.4	1022	13	13	-0.7
Hard Rock Casino		1.5m	4.4	0	33.4	1021	14.6	14.4	-2.2
		7m	7.9	3.4	40.8	1020	13.7	13.6	1.5
1550 Beach		1.5m	3.9	0.3	37.2	1019	15.3	15.3	0.9
		7m	7.2	3.1	48.9	1019	13.6	13.6	3.8
President Casino	12/3/2005	1.5m	7	5.2	63.1	1015	22.6	22.7	14.6
		7m	8.1	1.4	50.4	1014	22.9	23.2	14.8
1550 Beach		1.5m	6.8	1.5	54.7	1014	24.3	24	13.7
		7m	12.1	3.4	62.4	1014	23.4	22.6	20.5

*Table 2: Meteorological data collected at flight locations 11/30/2005 – 12/2/2005 (*** - data not recorded)*

While wind and weather conditions are a broad and complex subject area, the primary consideration for this line of research is turbulence. During any given flight near a building, it would not be uncommon to encounter downdrafts (typically found at the outside of a rotational cell on the lee side of a building), wind shear (when ascending through the roofline on the lee of the building), and general turbulence and eddied flow (common near corners). And since any semi-autonomous platform should be build to handle the the worst case conditions, these wind conditions should be accounted for when designing and setting specifications for a platform. How much downdraft is generated by a given wind speed and building type? When descending from a moving mass of air, to a still mass of air, what effect does this have on lift and control? And ultimately how much do the answers to these questions (and many other questions) effect the maximum vehicle speed, and attendant sensing requirements?

FEATURES

During the Biloxi survey operations, it became apparent that there were several features that a fully semi-autonomous MAV would need to be successful (and a few that would not be needed). This is a list of those features and a few comments.

The first, and perhaps most obvious is return to last known good communications point. With a semi-autonomous MAV, where control shared between the pilot and the embedded system, the possibility exists that the helicopter could move itself out of communications range of the pilot; in addition to that, a pilot can easily fly a helicopter out of range without any help from the computer. If the MAV looses radio link with the pilot, it should backtrack its recent path until it comes back within range, or alternately, simply begin flying back towards the launch point (though this does present some difficulties in complex urban environments).

Another important feature would be location hold. Particularly in imaging applications, stability is an important attribute of the platform. The further the helicopter gets from the pilot, the harder it becomes for the pilot to hold the helicopter in a precise hover. With appropriate sensors, the MAV should be able to perform this task for the pilot (even in a GPS denied/limited availability scenario). Some research groups have already demonstrated GPS hover, where the helicopter holds on a set of coordinates. This is not the same thing. The desired functionality, and something more useful in real life urban operations, is more akin to 'Hover here', rather than 'Hover there'. When the pilot and and mission specialist find a useful position, the pilot should be able to hit a switch to tell the helicopter to hold the position.

During the survey work, human-controlled hover was even one more step removed from a GPS style hover. Usually the reason for a hover was because that point afforded a good vantage point for the desired images. But, rarely was it that point only, but something closer to a 2-3m bubble which was pretty good. Often, somewhere in this region provided more favorable winds to holding a hover, so an operational hover was closer to an opportunistic regional function, as opposed to an absolute position.

Which segues directly to the final feature in the list, or rather the unfeature; GPS waypoint navigation. This may be useful for the Global Hawk, but it would not be used in a MAV platform. Search or survey work with a MAV size platform (particularly rotorcraft USAR) is highly opportunistic in nature. Usually you can see the target from the ground, or have a fair idea where it is, and just need a closer view, or a different vantage point. When the target is in view of the operator, and the maximum effective range of the system is less than 400m, it would only waste time to try to establish GPS waypoints for a mission. And in addition to being opportunistic from the ground, MAV operations are opportunistic from the air as well. Based on any number of conditions (including wind as previously discussed) the targets for a given flight may present themselves in a different order, or once airborne, a new target may present itself mid-flight.

VI. CONCLUSION AND FUTURE WORK:

Currently there are several communities where MAVs have the potential to become a critical tool for gathering tactical, over-the-hill intelligence. To do this effectively will require semi-autonomy from the aircraft, particularly helicopters, and the heart of this capability is obstacle-avoidance. A recent expedition to Biloxi, MS to survey damage from Hurricane Katrina presented an opportunity to investigate the requirements of such a behavior. This paper classifies operational conditions, including obstacle types, physical access, and obfuscated hazards, sensor requirements, wind conditions, and begins to explore some useful features for any helicopter MAV implementing semi-autonomy.

The next step in this research is to establish hard, quantitative answers to these questions (required sensor range and resolution, onboard computing capability), selecting usable sensors, and incrementally integrating this onto the IP3 platform.