The Quest for Indoor Flight

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ABSTRACT

Just as birds and insects are not found flying during adverse weather events, neither should micro air vehicles (MAV). Better assets exist for the conduct of outdoor unmanned aerial system missions than MAVs, however no assets exist for rapid ingress and reconnaissance of buildings, caves, and deeply buried underground facilities. This paper explores the characteristics of these mission spaces and shows why the real niche for the micro air vehicle is as an indoor asset.

INTRODUCTION

Back in 1997, the Defence Advanced Research Project Agency's (DARPA) vision for micro air vehicles (MAV) was that the individual soldiers at the platoon, company, or brigade level would use such vehicles for reconnaissance and surveillance, battle damage assessment, targeting, deploying sensors, communications relays, or for sensing chemical, nuclear or biological substances. These 15 cm vehicles would be able to conduct real-time imaging, have ranges of up to 10 kilometers, and speeds of up to 30 miles per hour for missions durations of 20 minutes to 60 minutes while carrying a payload of 20 grams [1].

By 2005, this ambitious goal is still unattained. The enabling technologies funded during the DARPA MAV program did not result in revolutionary advances nor has propulsion technology advanced sufficiently since then for the DARPA-envisioned performance levels to exceed the minimum expectation today.

Compounding the problem is the fact that the expectation for MAVs has been misfocused. The DARPA vision was for a predominantly outdoor asset. However, the same forces of nature that discourage insect and bird flight during thunderstorms, are also at play when considering MAV flight. One might ask, is it tactically practical to expect soldiers to wait until the wind stops blowing before they can look for the enemy over the next hill? Warfighters must engage the enemy in all weather, not just calm sunny days [2].

Further, does size really matter in the "over-the-hill" scenario? Because not all technologies are scalable, frequency limitations will be placed on MAV operations that impact navigation and communication. Were a soldier to send his MAV only 1 km ahead of his current position to look over a 30 m hill that is 60 m away, it would have to attain an altitude in excess of 500 m above the target area in order to avoid occlusion by the hill while maintaining line-of-sight with the soldier's ground control station. At this altitude the MAV would be neither seen nor heard... but neither would a larger air vehicle of perhaps ten times the size, as has been demonstrated on many occasions by existing "mini drones" such as the Aerovironment Raven or the Lockheed Martin Desert Hawk III (see Figure 1). The difficulty in flying at the 15 cm scale is therefore unwarranted not only due to the difficulty in negotiating weather with marginal endurance, but also because fielded assets already exist to address this mission.

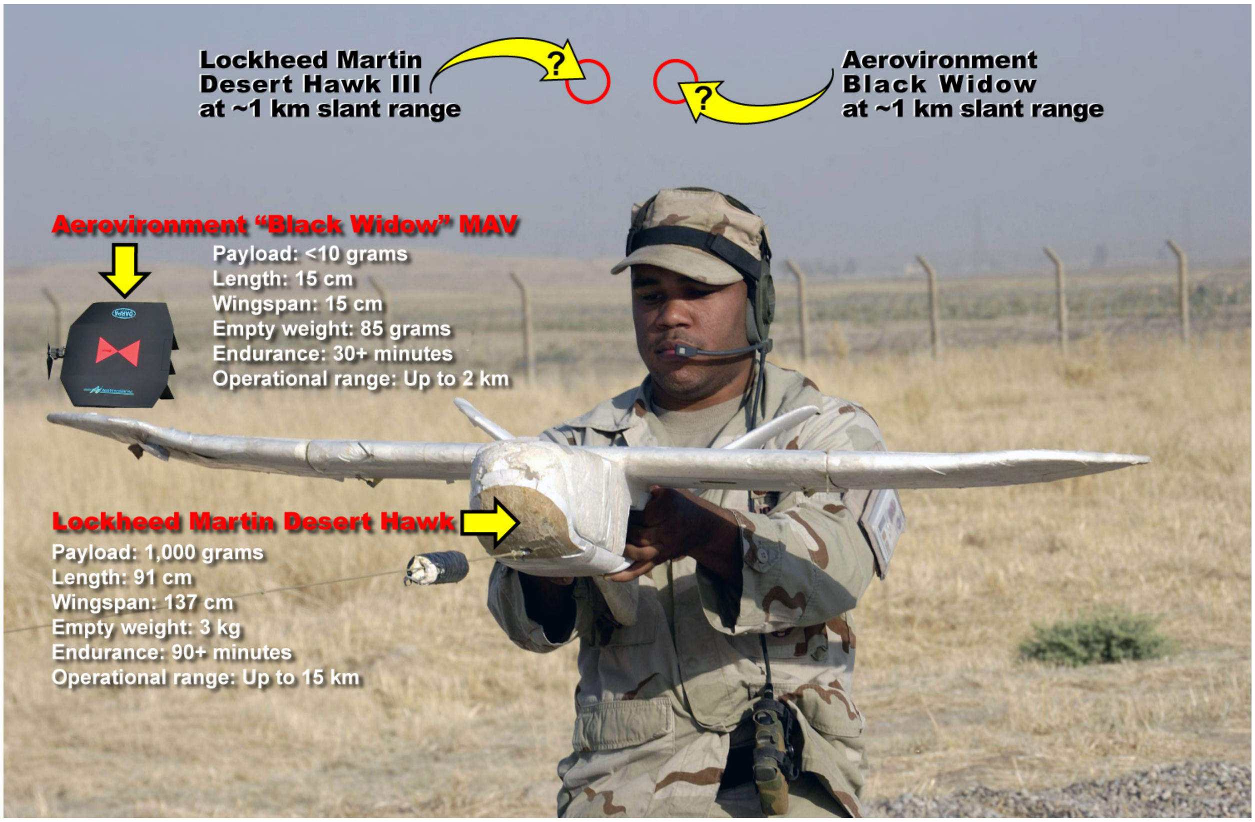

Figure 1. Simulated comparison of the Desert Hawk mini drone and the Aerovironment Black Widow MAV flying at 500 meters above ground level at a range of 1 km (1.118 km slant range).

THE REAL MISSION FOR MAVS

Assets exist for outdoor aerial reconnaissance. Experiments have shown on numerous occasions, including operations such as those in Iraq and Afghanistan, that *conventionally*-sized UAVs often go unnoticed when flying at several thousand feet over their targets. The state of the art in optics is such that high resolution video and infrared images can be gathered unobtrusively from platforms that exist today (e.g., Predator, Global Hawk). "Tiny" has additional stealth advantage, but carries an unwarranted cost when considered as a replacement for existing assets performing outdoor missions. This cost is not only in dollars, but in the ability to perform missions under even moderate weather aberrations. The real issue to be addressed is how to get the intelligence to be gathered under the control of, and into the hands of the individual warfighter. "Tiny" is only one of several possible solutions to addressing that goal. For example, multiplexing the Predator sensors to take snap shots of specific regions of the battlefield and to deliver them in near real time to the individual users who request them, is probably an easier and better integrated approach to C^3I than putting tiny personal air vehicles in the hands of the warfighter.

The real mission niche for tiny intelligent unmanned aerial vehicles will be indoors where the environment is controlled, and there are *no* existing reconnaissance craft that can rapidly negotiate hallways, crawl under doors, or navigate ventilation systems in an attempt to quickly penetrate deep into a building to complete a reconnaissance mission. It is the urban *indoor* mission that will ultimately justify the development expense. The very nature of an indoor mission will necessitate (1) multimode vehicles (flying/crawling/rolling/swimming), and (2) autonomous navigation.

It is desirable that these miniature automatons be not only small but possess multimode locomotion like insects, so they can move more freely and rapidly through a maze of obstacles, under doors, or inside otherwise inaccessible conduits. Size is important to a multimode robotic vehicle when negotiating indoor terrain. But it is also important when considering that operations in the indoor environment place the aerial robot in much closer proximity to its target than would ever be expected during outdoor operations. Therefore the stealthiness of small size becomes a significant feature for indoor operations.

SYSTEMS FOR FLIGHT IN CONFINED AREAS

A MAV operating indoors must be autonomous. Due to the size of the MAV, it will be difficult to support the long antennas necessary to communicate at lower frequencies. The higher frequencies which can be easily supported are more susceptible to attenuation through walls and become very directional (requiring line-of-sight with between transmitter and receiver) as the frequency of operation increases. Teleoperation once within a building is precluded not only by the physics of signal propagation, but also by the inability of a remote operator to see the MAV or know its location. GPS is not an option for navigation because the required antenna may be too large to be carried by very tiny vehicles and the GPS signal strength is too weak to be reliable inside a building.

Through the use of homing behavior however, the MAV can find its way around within buildings as it seeks particular chemical scents, acoustic sources, or strong RF emitters. It could also use dead reckoning to move down corridors and into rooms if there is an a priori knowledge of the building.

Critical to autonomous navigation will be obstacle avoidance. A sense of where the floor and walls are is essential. Knowledge of ceiling height is of lesser importance as the MAV could be programmed to fly at a predetermined altitude using the floor as a reference.

Only short range obstacle avoidance is really necessary. When flying down a corridor, the fact that a wall is 3 meters from the MAV is of little significance. Only when the MAV approaches to within some minimum distance dictated by the MAV's ability to maneuver, should a correction be needed. This implies that any ranging system need only operate over the short distance that exceeds the flight control sensor system latency, actuator latency, and vehicle response dynamics (flight envelope).

AUTONOMY IN MICRO AIR VEHICLES

Autonomous Flight Control in Micro Air Vehicles is important for nearly all operations because the size of vehicle is such that visual tracking for teleoperation is difficult at ranges beyond tens of meters. Teleoperated flight of micro air vehicles in open spaces has been demonstrated with the Aerovironment Black Widow where the pilot viewed the flight through an onboard camera system, but this presupposed slow or stabilized vehicle dynamic response, the ability to note the horizon, and general visibility. Night flights, flying in clouds, aerosols, or precipitation would not be possible, and even under good flight conditions, were the vehicle to go into a radical nose up or nose down attitude, or were the vehicle to be in a flat spin, it would be unlikely that a teleoperator could stabilize the vehicle rapidly, if at all. Fixed wing MAVs with maximum dimensions of 15 cm or less are particularly prone to gust-induced roll instabilities further exacerbating manual flight control.

When considering flight close to obstacles and in confined spaces, the ability of a teleoperator to make attitude and navigational corrections may be limited by his response time relative to that necessary for obstacle avoidance. Flight indoors by fixed wing vehicles, due to their speed, maneuverability limitations, and inherent instability is impractical except in large open indoor spaces. Rotary wing and flapping wing vehicles, being able to maintain flight at slower speeds allow a teleoperator to compensate for some of these impracticalities, especially if as in the case of some rotary wing vehicles, the airframe is dynamically stable in near-hover.

Still, non-line-of-sight teleoperation requires links to transmit teleoperator feedback pictures out of the confined area (a building, cave, or underground bunker). Transmission of energy from the MAV may not be possible due to the signal attenuation posed by surrounding obstacles and the onboard energy required to support such continuous real-time transmissions.

Autonomous operation for MAVs operating in confined spaces is the preferable approach for the following reasons: latency, energy, and aperture.

Latency

Latency of obstacle avoidance involves the time for (typically) an optical sensor to survey the MAV's immediate environment, relay pictures back to a remote non-line-of-sight teleoperator, processing of the image data to decide what control inputs are necessary, actuation of a command sensor (joystick, voice command, etc.), transmission of the commands, reception and interpretation of the commands by the MAV, control surface actuation, and delay in vehicle response in accordance with its flight envelope dynamics. When in proximity to obstacles (perhaps only several vehicle lengths distant), the latency in the teleoperator control loop may be beyond the limits of stable collision-free control.

On the other hand, were the MAV to be equipped with an adequate obstacle avoidance sensor suite, the latency due to the relay pictures back to a remote non-line-of-sight teleoperator, actuation of a command sensor (joystick, voice command, etc.), transmission of the commands, reception, and interpretation of the commands by the MAV are eliminated. The human decision-making process is by far the greatest source of latency for short range operations. A fully autonomous MAV will always be able to sense and respond to the presence of obstacles much faster than any human teleoperator.

Energy

Energy required to support feedback transmissions to a remote non-line-of-sight teleoperator is also a significant concern in the design of an efficient MAV. Energy is at a premium just for flight operations. Additional energy to support transmissions having enough power to penetrate the walls of a building or the ground itself in the case of a deeply-buried underground facility, will require additional onboard energy which translates into extra weight. This extra weight manifests itself in a decrease in mission endurance. Further, the need for high bandwidth (video) transmissions through attenuating obstacles will serve to limit useful mission range unless more powerful, heavier transmitters are used (the weight not coming so much from the transmitter, as it is from the supporting energy storage source which is typically a battery).

Aperture

Antenna aperture is also of concern. If a teleoperator requires wide bandwidth (video) non-line-of-sight transmissions through attenuating obstacles, the transmission technique used will need to support frequencies that can penetrate the obstacles (implying lower frequencies) while maintaining enough system gain to transmit and receive feedback and command inputs. Bandwidth, lower frequencies, and antenna gain all imply a larger physical antenna aperture. A MAV however, is limited in its dimensions and must maintain a high degree of aerodynamic efficiency. Because of limited wing and propulsor area, MAVs are not very efficient aerodynamically to begin with. Adding antenna appendages larger than the MAV itself is impractical. Ideally, MAV structures of maximum dimension (wing tip-to-wing tip, for example) afford the largest aerodynamic support structures for integrated antennas. Even so, with a limit of 15 cm, the maximum antenna aperture available drives efficient RF antenna designs into frequency regions of relatively high attenuation.

The elimination of wide bandwidth antennas is a better approach from the standpoint of weight (energy storage), and latency. Fully autonomy achieves improvements in both areas.

Self Stability

Full autonomy implies that the MAV can not only find its way around in confined spaces with no a priori knowledge of the environmental geometry, but also that the vehicle be able to maintain its own stability. The ability to navigate apart from external aids such as GPS is discussed below, but in many ways is less critical than the ability to maintain a stable vehicle attitude. MAV stability in flight can be achieved by several means, but all rely on past or present references. One approach would be to enter a confined space with a valid reference datum. Unfortunately the best gyroscopes and accelerometers will in time drift due noise sources within the references themselves. Depending upon mission duration, these references will become so skewed that stable flight is no longer possible without resetting the reference memories to correspond to a reference datum.

Fortunately, in many situations where obstacles are man-made, there is a proclivity to have vertical and horizontal surfaces. A priori knowledge that the environment will be culturally-inspired can be exploited to allow updating of onboard reference memories as the mission progresses. Range detection sensors (radar, sonar) can not only identify the vehicle position in three-space, but can also provide input as to vehicle attitude.

CLOSE QUARTERS OBSTACLE DETECTION AND AVOIDANCE

Close Quarters Obstacle Detection and Avoidance is usually line-of-sight. This can be of significant advantage to MAVs since the use of higher powered longer range sensors increases the stored energy burden of the MAV. Further, short range line-of-sight obstacle detection using high frequency electro-optical techiques (EO/IR) or acoustic techniques is possible because the free space attenuation of the signals at these frequencies is minimized. Techniques such as RF-based radar, EO/IR-based ranging, acoustic sonar, or passive stereo vision (RF, EO/IR, or acoustic) are all candidates for use in creating a real-time situational awareness map surrounding the MAV.

Onboard processing is key to obstacle avoidance in that a degree of interpretation is required beyond mere environmental perception. At the lowest level, autonomic (reactive) responses to obstacle Doppler, obstacle size increase, or obstacle proximity can elicit evasive maneuvers. Such autonomic responses override the navigation plan and any motivators that drive a MAV's homing response. At a higher level of intelligence, algorithms can be employed to analyze sensor data to plot a course through the maze of obstacles populating the MAV's world. In this case, obstacle avoidance is planned rather than reactive. It becomes part of the navigational solution that factors in directional motivators (homing, map following, or simple preprogrammed search patterns).

Sensitivity limits can be set by which autonomic reactions take place so as to respond while still within the maneuver envelope of the MAV. Planned avoidance has the advantage of time to replan based on the appearance of unbriefed obstacles, but presupposes that the obstacle sensors are able to detect the obstacles at a reasonable standoff distance and that the latency of the interpretation algorithms is sufficient to render a solution with adequate time to remain comfortably within the bounds of the maneuver envelope.

In some cases, autonomic reactions could devolve into a situation in which multiple local minima are encountered that trap the vehicle into a safe, but redundant avoidance path from which it can never emerge (perhaps flying in a circle around an object or within a small room at the end of a hallway (see Figure 2)). This might occur with a simple reactive wall-following algorithm where only the MAV altitude and obstacles ahead of, and to the right side of the MAV are sensed with the response always being to "turn left" when an obstacle is encountered ahead.

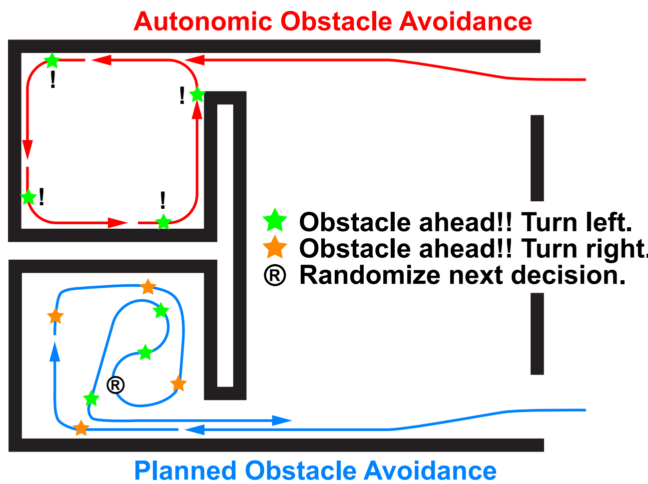

Figure 2. Autonomic trap vs. response randomizer.

A more robust technique would involve spherical, or at least hemispherical environmental perception with a standoff detection range exceeding the minimum maneuver envelope of the MAV. Introduction of random variables to allow the navigation algorithms to plan alternate acceptable avoidance paths (rather than eliciting an identical response to the same sensor data every time it is encountered) can allow the MAV to break out of redundant behaviors into productive emergent behaviors that lead to the same mission goal (see Figure 2).

INDOOR NAVIGATION APART FROM GPS

Most guidance, navigation, and control (GNC) algorithms for UAVs presuppose the availability of the Global Positioning System (GPS). The indoor mission space where MAVs make the most sense will be devoid of GPS cues and an autonomous MAV must be able to navigate and maintain stability by other means.

GPS is most widely known as a navigation aid, however it also provides universal time cues and can be used to derive vehicle velocity as well as vehicle attitude when high resolution techniques are used. The GPS signal can correct for inertial navigation system (INS) biases, noise, and initial misalignment errors. A comparison of the position and velocity obtained by integrating the accelerometer output (in the case of a strap-down INS) with the same parameters measured from the GPS signals can be used to generate error values. Using the error between the physical INS and the calculated GPS reference allows a Kalman Filter to concurrently estimate INS biases and correct for INS drift errors.

No physical INS is necessary if GPS is available however. For example, in 1995, the Stanford University team participating in the 5th annual International Aerial Robotics Competition on the campus of the Georgia Institute of Technology was able to not only navigate, but stabilize their small helicopter-based aerial robot through the use of GPS signals alone [3]. The helicopter had no inertial components such as gyroscopes or accelerometers. It was using carrier phase-referenced signals from the GPS satellite constellation to achieve centimeter accuracies that allowed the helicopter to know not only where it was with great precision, but also whether its right side was higher or lower than its left side for roll determination, and whether the nose was lower than the tail boom (for pitch determination).

MAVs operating indoors will not have access to GPS and must therefore use either a local GPS-like reference, inertial memory, or cues from the environment. In practice neither GPS-like references will be available in denied indoor areas, nor will inertial memories be able function for extended periods (usually only minutes) without drift-induced degradation. The indoor MAV must achieve attitude stability and navigation cues from its environment.

This is not unreasonable when one considers that birds and flying insects are able to fly indoors without a priori knowledge of the environment. They do not flip over and crash, nor do they run into obstacles. Clearly, their onboard sensors and processing allow them to operate with some success indoors without reliance on GPS. MAVs will have to operate using similar cues to those of birds and insects, namely: the gravitational vector, range estimation to obstacles, obstacle recognition type 1 (“is that dark image a hard object or hole through which I can fly?”), obstacle recognition type 2 (“is that object a threat or is it potentially useful?”), acoustic cues, air flow direction. This is all in addition to the motivational sensing that drives the MAV to its mission destination.

LOW POWER COMMUNICATION AND SENSING IN SPECTRALLY-CLUTTERED ENVIRONMENTS

As discussed earlier in this paper, energy is at a premium onboard a MAV. Transmissions expend energy and must be efficient. Transmissions may be for communication with the outside world and may involve mission-critical information, but they may also be for active ranging of nearby obstacles during navigation or for altimety, or for stability in flight (attitude sensing relative to assumed cultural items (horizontal floors/vertical walls)).

Buildings contain large flat reflective surfaces that can present low reflectivity for ranging due to signal impingement angle, or they can provide a significant source of multipath reflection. Transmitting in such an environment for the purpose of communicating with the outside world may be frustrated by the attenuation of the building as well as the free space losses encountered at the high frequencies supported by tiny MAV antennas. Transmitting for the purpose of interrogating the surrounding environment may be difficult due to the proximity of large reflectors.

The use of spread spectrum transmissions and signal processing may present a way to circumvent both the communication and navigation transmission problems. Small conformal antennas can be optimized for wide bandwidth transmission and reception of omni-directional RF signals. EO/IR systems, because of their very high frequencies of operation can have higher gain focused emitters and receivers than useful RF systems, but can suffer from greater spectral clutter in complex near-field environments. Acoustic transceivers will fall somewhere between RF and EO/IR in terms of interference from cultural clutter.

Also to be considered is noise of various types. Indoor environments can have powerful unintentional jamming sources for RF, EO/IR, and even acoustic systems. Again, where possible, the use of spread spectrum techniques with correlation processing can overcome very large cultural noise sources.

SURVIVABLE AIRFRAMES AND PROPULSORS IN OBSTACLE-RICH ENVIRONMENTS

Indoor MAV missions will typically involve flight in unknown or unmapped surroundings having unbriefed obstacles. Conventional fixed wing MAVs will be the least useful due to their flight speed and inability to land and takeoff without space to gain airspeed. Tail sitters may be able to land and takeoff, but the issue of flight speed and reaction time to avoid obstacles remains.

Some have proposed lighter than air (LTA) MAVs for indoor operations because of their quiet stable flight characteristics, however an LTA MAV is a contradiction in terms due to the small amount of mass that can be supported by even a hydrogen envelope of 15 cm or less. An envelope fitting within the classic definition of a 15 cm MAV would be able to support only 1.84 grams (when using helium). That would include the envelope, propulsion, energy storage, and sensors. This is comparable to a large insect except for the fact that there is a 15 cm spherical balloon with its attendant aerodynamic drag. Such a LTA vehicle would not be able to support enough propulson power to overcome the slightest airflow from air ducts or other sources. In fact, LTA vehicles become more impractical as size decreases.

Rotary wing and flapping wing MAV configurations are the best choices for indoor missions because they can fly slowly, hover, and can land and takeoff in small spaces (perhaps vertically). They suffer from less efficient flight since aerodynamic lift is only achieved through motion of the wing/propeller/rotor (they can not glide). They also have the potential for catastrophic failure if their moving propulsors touch obstacles. Correct design of rotary wing MAVs will surround the propeller/rotor with either a shroud or a protecting ring to prevent impact with obstacles. The associated drag and weight penalties accruing from these survivability measures is offset by the ability of the rotary wing MAV to not only approach obstacles with impunity, but also to physically contact them.

Flapping wing MAVs can not realistically employ shrouds to protect the flapping wing propulsors, however just like birds and insects which can briefly impact obstacles and walls without damage, a flapping wing MAV can be constructed from flexible wing materials that can sustain grazing impacts without damage. Unlike a rotor or propeller which contains all of its energy at essentially a single frequency of rotation, a flapping wing goes through a cycle of maximum velocity bounded by two periods of zero velocity. This, coupled with the wider chord of flapping wings makes the wing a lower energy propulsor than a rotor at any given point along the wing for an equal degree of lift force. An impact that would cause a rotor to explode, would likely just push a flapping wing away from an object. If the flapping wing is then made to be compliant, it will also tend to bend rather than break. This is exactly what is observed when bird wings graze walls.

CONCLUSION

The mission niche for MAVs is indoors due advantages of size in close proximity to obstacles. Better assets exist for outdoor UAS missions as the need for small size becomes a disadvantage in terms of endurance and payload capability, while flight in wind and precipitation is problematic. Special attention must be paid to the sensor suite used indoors as it must be able to operate reliably in spectrally cluttered multipath environments. Autonomous operation is essential in the absence of GPS cues and the inability of a teleoperator to efficiently control a MAV under non-line-of-sight conditions where split second decisions are necessary to avoid collisions. Both rotary wing and flapping wing MAV implementations have inherent advantages over other aerial robotic morphologies when operating in confined spaces.

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