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Test and Evaluation of Fully Autonomous Micro Air Vehicles

Robert C. Michelson
President, *Millennial Vision, LLC*
Principal Research Engineer Emeritus
Adj. Associate Professor, School of Aerospace Engineering (ret)
Georgia Institute of Technology
Atlanta Georgia

The test and evaluation of unmanned systems presents special challenges, but these challenges are amplified when one moves into the realm of micro air vehicles. Further complications arise when these MAVs are fully autonomous. The following discussion explores the difficulties in testing not only the physical flight characteristics of small flying things, but their behavioral characteristics as automatons. A fully autonomous flapping wing micro air vehicle known as the Entomopter will be used as a robust example that embodies a greater range of operation than typical fixed wing MAVs.

MICRO AIR VEHICLES (MAV)

"'Micro Air Vehicle' is a most unfortunate name given to this class of air vehicles because none are truly "micro" and the original official Defense Advanced Research Projects Agency (DARPA) vehicle definition requiring a maximum 15 cm dimension confirmed the name to be a total misnomer."[1]

Originally touted by the military as an asset that could be carried by every war fighter (thus enabling the soldier to "see over the next hill" on a moment's notice) and packaged like an MRE (meal ready to eat), the MAV has proven to be a more elusive panacea primarily due to its small, albeit not 'micro', size. Since MAVs are on the size scale of a small bird, they are not rugged because they must be light enough to fly while exhibiting a useful endurance. Being small and light, they are thus at the mercy of weather effects, most notably wind, and to a lesser extent, rain. Their small size also dictates antenna aperture size, which normally can not greatly exceed the maximum dimension of the MAV. Therefore, communications frequencies must be higher, and hence, more directional in order to achieve reasonable link margins.

Another serious drawback is command and control of an air vehicle which can not be seen by an operator at distances greater than about 50 m. Command and control is also limited by the available onboard energy that can be devoted to in-flight video transmission for teleoperation.

A solution to these problems is autonomy. A fully autonomous MAV containing sufficient onboard intelligence to carry out useful missions has various advantages including:

- Extended range because high frequency line-of-sight (LOS) links are obviated
- Quicker reaction time to atmospheric perturbations and obstacle avoidance than can be afforded by a teleoperator
- Potentially greater stealth due to lower bandwidth emissions
- The ability to operate indoors or in urban canyons where communication is not possible
- Jam resistance
- The potential for beneficial emergent behaviors leading higher probability of mission success

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Difficulties in testing these tiny MAVs falls into two categories when they suddenly are given the power of autonomy: physical flight testing and behavioral testing. To exemplify some of the issues involved in each, consider the flapping wing MAV known as the Entomopter.

The Entomopter was designed from inception to be a fully autonomous MAV for use in indoor reconnaissance. Initial development was begun at the Georgia Tech Research Institute by the author under and IRAD program, and was later funded by DARPA's Mesomachines program to demonstrate feasibility of such a device for indoor flight. The Air Force Research Laboratory then provided funding to extend the Entomopter's chemically-fueled propulsion system into its fourth generation. Subsequently, the NASA Institute for Advanced Concepts became interested in the Entomopter's unique flight capabilities which make slow flight in the lower Mars atmosphere possible. A feasibility study was then funded to show how an Entomopter-based Mars Surveyor could enhance the science missions envisioned for Mars.

All of these programs involved analytical substantiation of the Entomopter in various environments ranging from low Reynolds number flight in Earth's lower atmosphere to low Reynolds number flight in Mars' lower atmosphere. Also common to these programs was the fact that the Entomopter was to be fully autonomous and never teleoperated. Full autonomy was essential for indoor operation where communication and global positioning system signals were not available, and it was likewise essential for Mars operations where the latency of control (10-15 minutes depending upon Mars' distance from Earth) necessitated a vehicle that could carry out missions unassisted.

THE ENTOMOPTER

The terrestrial Entomopter (see Figure 1) is a multimode autonomous robot capable of flight and limited ambulatory behaviors. Autonomous navigation is based on a combination of attraction and avoidance behaviors deriving input from both an integrated optic-olfactory sensor for detection of chemical species (or, alternatively, a sensor for a specific type of radiation), and an ultrasonic swept beam ranging device.

The terrestrial Entomopter eventually found potential applications on Mars by virtue of its unique "blown" flapping wing [U.S. Patent No. 6,082,671 and U.S. Patent No. 6,446,909]. Present planetary surface rovers have shortcomings that NASA could address with a slow flying aerial platform, however flight on Mars is complicated by the fact that the atmosphere is rarefied, thereby making it difficult to generate lift with conventional wings. In fact, fixed wing vehicles must have enormous wings and travel at speeds in excess of 300 kph to stay aloft in the Mars atmosphere.[2] Turn radii are on the order of kilometers, making it inefficient to return to points of interest, and high speed traverse across the surface at lower altitudes causes smearing of sensor data, thereby negating any beneficial increase in resolution that may have otherwise been gained.[3]

NASA recognized that the Entomopter's ability to fly in low Reynolds number conditions without the need for air-breathing propulsion made it a natural candidate for flight in Mars' rarefied atmosphere, albeit in a larger incarnation. Unlike fixed wing flyers, an entomopter-based Mars surveyor would be able to cover a wide area while still being able to fly slowly and return to a refueling rover.

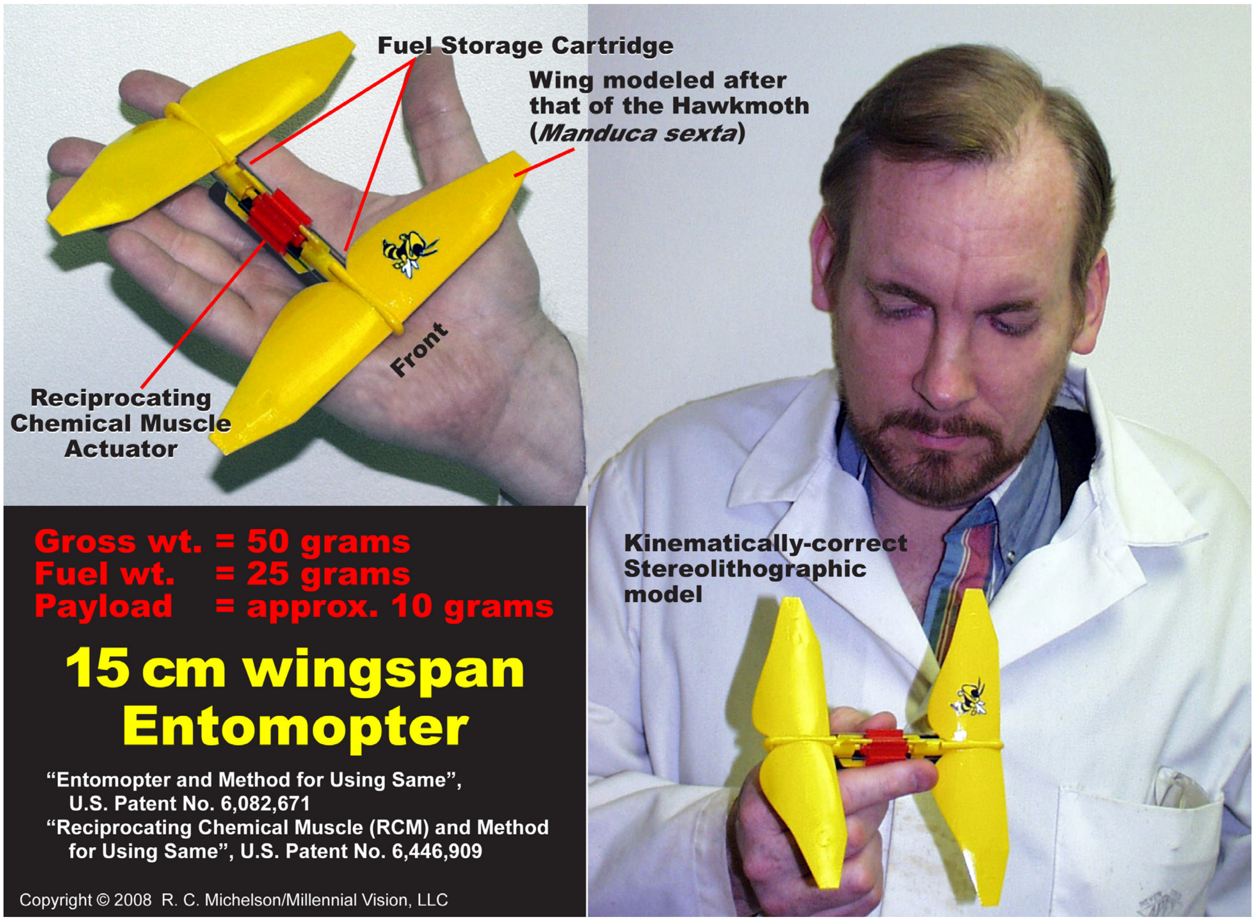

Figure 1. 15 cm terrestrial Entomopter.

The Entomopter began as a biologically inspired design, but rather than attempting to replicate biological kinematics and aerodynamics, improved systems have been devised to leverage what is observed in biological systems to produce a machine that is manufacturable, controllable, and able to generate the power necessary to fly from onboard energy sources.[1]

The Hawk Moth (Manduca *sexta*) was chosen as a baseline model for the wing aerodynamics. The University of Cambridge in England was part of the initial Entomopter design team because it had studied Hawk Moth wing aerodynamics for more than a quarter of a century and had produced seminal works describing the Leading Edge Vortex (LEV) and its effects on the flapping wing. [4][5][6][7][8] The flapping mechanism for the Entomopter has been extended beyond that of the Hawk Moth to provide a resonant single-piece construction that takes advantage of torsional resonance in the Entomopter fuselage to recover flapping energy common to flying insects that temporarily store potential energy in either muscles or exoskeletal parts (resilin).

In the terrestrial version, the same structure that provides wing flapping also scans a frequency modulated continuous wave (FMCW) ultrasonic beam to provide front, side, and down-looking range measurements for obstacle avoidance and altimetry. It also has the potential to track and follow free-moving agents in a fashion similar to that employed by bats.

Stability and control in flight as well as navigation are achieved by actively modifying the lift of each wing on a beat-to-beat basis using pneumatic control of the air circulating over the beating wing. Also, as demonstrated in GTRI's wind tunnels, where pneumatically controlled wings have been shown to develop positive lift at negative angles of attack (α) as great as -70°,[9][10] Entomopter wings (unlike those of the Hawk Moth) should be able to generate positive lift not only the downbeat but the upbeat as well. These wind tunnel tests have shown that coefficients of lift exceeding the theoretical maximum by 500% for the given wing shape can be achieved without the complexity of active angle-of-attack modulating mechanisms.[11]

A chemically fueled reciprocating chemical muscle has been designed and is in its fourth generation of development. This actuator system has demonstrated 70 Hz reciprocation rates with throws and evolved power levels necessary to support flight of a fully autonomous Entomopter system.[12] The reciprocating chemical muscle uses the energy locked in various monopropellants to produce reciprocating motion for propulsion as well as waste gas products for the operation of gas bearings, an ultrasonic obstacle avoidance ranging system, and full flight control of the vehicle.

TESTING MAVs (Physical realm)

Rigorous testing of MAVs usually begins in a wind tunnel with airfoil sections and eventually the entire air vehicle. A problem in wind tunnel testing is that many tunnels are not configured to handle such small test objects and the balances may not have the desired resolution to see what is going on under various test conditions. Further, the low Reynolds numbers at which MAVs operate pose scaling problems. Most MAVs in the DARPA 15 cm size region are at the transition between classical aerodynamics and low Reynolds number aerodynamics. As has been observed in certain thin airfoil low Reynolds number experiments at the University of Bristol, external acoustic energy can actually affect the measurements.[13]

One advantage that MAVs offer during wind tunnel testing is the ability to easily power the model in order to get true readings concerning the forces involved and the behavior of vortices over the entire body of the craft. Powered wind tunnel testing is facilitated when considering fixed wing and rotary wing MAVs, however the same tests on a powered flapping wing MAV becomes problematic. Conventional flapping wing MAVs induce vertical loads into the wind tunnel balance which are larger than the aerodynamic wing forces being measured. This requires the development of a special balance that can withstand the inertia of the wing/body interaction while still being able to sense the minute aerodynamic forces created by different flow regimes over the wings and fuselage. The Entomopter has flapping wings, but there are two sets of wings flapping equally and oppositely across the fuselage as a fulcrum (like two seesaws 180 degrees out of phase). As a result, it is one of the few flapping wing designs that can be tested with a conventional wind tunnel balance designed for fixed wing MAVs. Control forces on the Entomopter wing are a result of differences in lift produced by circulation-controlled air foils which employ the Coanda Effect to increase wing lift by keeping flow attached, or decrease it by allowing the flow to detach into shed vortices. The effect as seen by the balance is similar to that of a conventional fixed wing with elevons.

Because of the low risk involved in MAV flight, air vehicle tests proceed from the wind tunnel to free flight out doors much sooner than with larger aircraft that can ill afford to crash during development. Free flight testing of MAVs suffers from the inability to adequately instrument the vehicle because of its very limited payload capacity. Most MAVs operate with 50% of their gross takeoff weight being energy (battery, fuel) and propulsion; the remaining 50% comprising the airframe and the payload. A 50 gram vehicle such as the terrestrial Entomopter devotes 25 grams to fuel and 15 grams to the airframe/propulsion system (which are highly integrated). This leaves a mere 10 grams for payload. The addition of test instrumentation will have to be at the expense of fuel and endurance. Unlike a fixed wing battery-operated MAV, the Entomopter has the luxury of consuming its fuel and getting ever lighter as the mission progresses, so a cutback in fuel to accommodate test instrumentation actually has less of an impact on endurance than its electrically-driven cousins.

Once in free flight, monitoring of the MAV becomes totally reliant on stored or telemetered data because the vehicle behavior to control inputs (whether teleoperated or autonomously generated) is largely unobservable from the ground. Because MAVs have short wing spans (or disk areas for rotary wing MAVs), they have low wing loading and are especially sensitive to roll induced by wind gusts. The mass moment of inertia scales as the fifth power of a given dimension, so the smaller the vehicle, the higher the bandwidth of the control system necessary to stabilize rotational instabilities. Analysis of in-flight oscillatory behaviors usually becomes a trial and error process where modifications to control surfaces and airfoils are made on the ground after analysis of the flight test data (as opposed to real-time adaptive control modifications). Again, this is a function of the inability to carry significant test payloads but is also encouraged by the relatively low cost and low risk of MAV free-flight testing.

The challenges increase by orders of magnitude when trying to test a planetary flight vehicle. In the case of the Mars Entomopter, Earth conditions actually preclude free flight testing because the Mars Entomopter would be optimized for the reduced gravity on Mars which allows a heavier vehicle to be used than that which would be possible on Earth.

Mars' atmosphere has a mean surface level pressure of 600 Pascals (0.087 pounds per square inch), compared to Earth's 101,300 Pascals (14.7 pounds per square inch at sea level). This makes flight on Mars very difficult. A conventional fixed wing flight vehicle would have to travel excessively fast (perhaps greater than 300 kilometers per hour) simply to stay aloft without stalling and plummeting to the surface, however at these speeds, detailed survey of the planet's surface is impractical as would be landing for refueling to extend the mission. The flapping Entomopter wings can in essence flap at more than 300 kph, and coupled with its circulation controlled airfoils that can generate lift up to seven times greater lift than theoretically possible for its wing shape, the Entomopter can fly slowly in the rarefied Mars atmosphere. A 15 cm terrestrial Entomopter flying in Earth's atmosphere is therefore equivalent to a 1 meter Entomopter flying in Mar's thin atmosphere. Since Mars' gravity is about 37% that of Earth, the larger Mars Entomopter can weigh three times as much as the terrestrial Entomopter and still fly like its miniature Earthbound cousin. An Entomopter with an approximate 1 meter wingspan, flies in the same Reynolds number regime (and therefore generates lift in the same manner) as small insects do in Earth's denser atmosphere.

So how does one conduct flight tests of a planetary flight vehicle here on Earth? In the wind tunnel, the air speed can be scaled to correspond to low Reynolds number flight for a given sized vehicle. Alternately, there are a few wind tunnels in the world which can be pumped down to a low atmospheric pressure to make unscaled measurements. Free flight is even possible by taking air vehicles to high altitudes and releasing them in the thin atmosphere at altitude.

Mars flight testing is still problematic because of the reduced gravity. A larger, heavier vehicle that might be used in Mars lower atmosphere, even if dropped from altitude, will still be under the influence of Earth's higher gravitational field. One suggestion that has been considered is to conduct wind tunnel tests in a pumped-down tunnel while using magnetic levitation to off-load the appropriate amount of vehicle wight. Still, this technique would suffer from inertial effects as some of the wight to off-loaded might be in the moving wing structures, the weight of which would be hard to control while in motion. The best solution to date is to design analytical models for testing, and then building surrogate testbeds that approximate the actual vehicle with full knowledge of the underlying assumptions.

TESTING AUTONOMOUS MAVs (Behavioral realm)

In addition to the testing of the physical performance of MAVs under controlled (wind tunnel) or real-world (free-flight) conditions, autonomous MAVs require another level of testing to assess intelligent behavior. Autonomous MAVs must ultimately perform a mission function effectively. MAV autonomy will be based on intelligent cognitive behaviors that direct to logically expected maneuvers leading to mission success. Cognitive systems may evolve "emergent behaviors" that may still lead to mission success, but in ways that are unexpected by the designer. Emergent (unpredictable) behavior is a consequence of a decentralized system with reactive properties, indicative of swarms of independent MAVs. The individual MAV's own high level cognitive system will gravitate towards centralized forms of behavior, and therefore, emergent behavior is less likely but still possible. This makes testing of autonomous MAVs an even greater challenge.

Autonomous MAVs will possess various behavioral traits which, when combined, will elicit useful high level behavior leading to mission success. These traits are discussed below:

Perception and Mobility

Autonomous MAVs must be able to perceive their environment and control their motion through it. To find their targets, for example, MAVs must be able to identify their goal through some means of object recognition, and move towards their goal based on a path planning algorithm that avoids threats (which may be physical obstacles or ephemeral things such as adverse weather or hostile agents). The more information that MAVs can perceive to assist them in navigating to their goal, the greater the odds of achieving mission success.

Temporal Reasoning

In order to succeed at their assigned mission, autonomous MAVs must perceive and reason about events that occur during various temporal intervals. The relations of these intervals to one another is important to the outcome of future events. For example, were a MAV to be tracking a moving target and the target moves behind an obstacle (becoming occluded) only to emerge from the other side of the obstacle moments later, it would be reasonable to assume that the newly acquired target is in fact the same target that was being tracked. The correct autonomous MAV behavioral response might therefore be to continue tracking the reacquired target rather than beginning a search pattern on the far side of the obstacle.

Logical Deduction, Falsification, Default Reasoning, and Explanation

MAV intelligence presupposes the fact that the MAV can draw conclusions from its perception. These conclusions may require deductions to be made based solely on inferences drawn from its world model and its finite body of stored time-weighted (most recent = most accurate) perceived data. Consider the terrestrial Entomopter tracking a moving object in a building. The object turns out to be a rat running across the floor. Suddenly the Entomopter loses track because the target disappears. The rat ran into a hole in the wall. The Entomopter must deduce from its observations that the target was lost at the point it intersected the wall. It must conclude as false, the assumption that the wall is a solid object. The Entomopter must then reason that the wall can be penetrated, so its explanation is that the target escaped its view by exiting through a hole in the wall. The behavioral response of the Entomopter might then be to give up the track or instead, it might begin a search on the opposite side of the wall if it has a path to the other side stored in its track history or perhaps it may even begin a search for a path to the other side in order to reacquire the target.

Testing for these kind of behaviors is very difficult in an autonomous system because there is no deterministic solution unless the observer has the same database as the MAV and even then, there may be several correct responses which might appear as emergent behavior on the part of the MAV. Questions such as "what can you assume and why" - "what does it take to falsify an assumption?" - "when there is more than one explanation for an event?" - "which explanation will the MAV choose?"

Belief Revision and Reason Maintenance

An autonomous MAV may find that it has to revise its beliefs based on contradictory facts. Because the MAV could have inferred more facts based on the originally assumed fact, revising its belief about the original fact is far more complicated than simply retracting it. The MAV must retract *all* beliefs it inferred using the original fact if they are not substantiated by independent facts which are still believed to be true.

Again consider the Entomopter tracking the rat that escaped through a hole in the wall. The explanation arrived at by the Entomopter based on its world model is that the rat has escaped from the current room into an adjoining room. In the process of searching for a path to the adjacent room, were the Entomopter to discover that the wall is not a single plane, but a hollow wall with two faces, it can no longer assume that the rat must be in the adjacent room. The Entomopter's onboard cognitive system must now revise its beliefs about the nature of walls, and in the process, discard assumptions that rooms are separated by a single solid plane with holes. In fact, the rat could be hiding "inside" the wall. Based on this new conclusion, the Entomopter may now decide that the cost in energy to continue the search for a path to the adjacent room may not be worth the expense because the likelihood of finding the rat in the adjacent room has been significantly diminished.

Planning, Searching, Problem Solving

Events often have more than one possible outcome and MAVs can execute more than one action at any given time. The sequence of possible inferences and actions about event outcomes creates an enormous space of possible world states. The MAVs onboard cognitive system must choose a sequence of inferences and actions to reach a desired state. In addition, because the MAV is a flying automaton, it can not hesitate in the making of these decisions. It does not have the luxury of stopping to think. Therefore, the cognitive systems employed by MAVs must be highly efficient in their ability to process data and draw conclusions.

Consider the Mars Entomopter returning to its refueling rover when it detects something moving on or near the surface of the planet (see Figure 2). Moving objects other than the refueling rover are not expected. Is the object in fact the refueling rover? Is it a dust devil? Is it alive? The Entomopter must solve this problem quickly because the object may be of paramount scientific importance, but on the other hand, the Entomopter is low on fuel and must assure that whatever action it takes will not jeopardize its ability to return to the refueling rover. The solution to the problem may lie in the relative location of the object, the appearance of the object, the speed of the object, and the apparent direction of its travel. This must be coupled with the amount of fuel remaining, the distance of the refueling rover from the Entomopter and from the detected moving object. Any information about headwinds will play a factor.

As the problem becomes more complex, the ability to test and evaluate the response as to its correctness, becomes very difficult. The problem presents various optional responses, some of which would be better than others, while some would lead to disaster. Due to the immense size of the problem space, such situations are ripe for the occurrence of unforeseen emergent behaviors and are practically impossible to test. Even in simulation, the selection of the given set of parameters defining the problem space will likely not match what is actually encountered during a mission. The best that can be hoped for is to correctly evaluate the behavior after the fact based on stored/recovered data in the hope that unforeseen bizarre behaviors can be eliminated in during future missions.

Figure 2. Mars Entomopter operating in the vicinity of its refueling rover.

Probabilistic Inference

In the real world where mission success or failure may result from more than one possible outcome, some events are more likely than others. "Uncertain reasoning" or "probabilistic inference" must be used by the MAV to decide which of the many outcomes is most likely when presented with scenarios involving several possible outcomes. Considering the previous example, were the Entomopter to have a priori knowledge that a storm is approaching and that its refueling rover is definitely located in the opposite direction from the presently unidentified object moving across the Mars landscape, the probability of that object being a weather related phenomenon (and therefore of lower interest) would bias the decision to continue toward the refueling rover.

Social Reasoning, Communication and Human-Machine Interaction

Under some circumstances, fully autonomous MAVs might be members of a cooperative "swarm" of other MAVs or might be a member of a network involving other autonomous systems (unmanned ground vehicles (UGV), ground stations, or even humans). When interacting with these other intelligent or even autonomous entities, the MAV must be able to reason about that entity's mental state. Depending on the entity type, this implies that the MAV's behavior will require it to consider the emotions, beliefs, desires, personality traits, etc. of the other entities with which it is interacting. The MAV's actions will depend to a degree, on the perceived responses of its counterparts. If the Mars Entomopter knows that its refueling rover is apt to stop upon sensing that the Entomopter is returning to refuel, then the Entomopter will adjust its flight approach accordingly. Alternately, were the Entomopter to attempt to land on unknown terrain, it would assume a degree of unpredictability about its touchdown location.

CONCLUSIONS

Micro Air Vehicles will incorporate greater degrees of autonomy as they increase in capability and popularity among the mainly military user base. All of the challenges associated with aircraft testing and evaluation are present with MAVs, but are compounded by the different physical environment in which they operate. The environment differs not only in terms of the mission space which unlike manned aircraft and larger unmanned aerial vehicles includes confined spaces such as urban canyons, building interiors, and natural formations such as caves, but also there is a difference in the very medium through which the MAVs operate: a more viscous, low Reynolds number environment.

Flapping wing implementations are more likely MAV implementations than for larger aircraft. The testing of flapping wing MAVs in the wind tunnel and in free flight presents special challenges.

The physical realm in which MAVs will be tested is therefore more challenging in many respects, but the fact that the entire vehicle with its propulsion system intact and operating in the wind tunnel, allows a level of convenience and accuracy which many not be present in larger test objects. These advantages evaporate when extraplanetary MAVs are considered however. Simulation of different atmospheres and particularly different gravitational fields is problematic.

When full autonomy is applied to MAV designs, the ability to test them in the behavioral realm becomes an even greater challenge due to the size of the MAV and the difficulty in monitoring and communicating with them in free flight. The payload capacity of MAVs is necessarily small, but the non-scaling items such as antenna apertures present the evaluator with serious real-time monitoring issues. As the MAV's level of cognition increases, predicting its behavioral response in a free-flight real world environment becomes statistically impossible in real time as the size of the problem space expands.

A recommended testing regime would decouple the physical realm testing from that of the behavioral realm. Controlled wind tunnel testing to corroborate simulations such as those derived from computational fluid dynamics (CFD) analyses will yield baseline performance results that can predict free flight behaviors given that actual conditions can be recreated in the wind tunnel environment. Free flight testing will then validate the controlled wind tunnel measurements.

Once the MAV is endowed with a sentient nature and cognition to interpret its perception of the environment with its assumed physical laws, our ability to "test" MAV behavior may be limited, and instead will devolve into more of an "evaluation" of observed behavior.

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AUTHOR BIO

Robert C. Michelson is a graduate of Virginia Polytechnic Institute & State University and the Georgia Institute of Technology with degrees in Electrical Engineering. He worked on aerospace radar systems at the U.S. Naval Research Laboratory in Washington D.C. prior to his 30 year career at the Georgia Tech Research Institute (GTRI) where as Adj. Associate Professor to the School of Aerospace Engineering he taught UAV/MAV avionics design. Michelson is currently Principal Research Engineer Emeritus with the Institute. In 2004 he created Millennial Vision, LLC to continue research into biologically inspired aerial robots and remote sensing (see http://angel-strike.com/rcmbio/RCM/MICHELSON.bio.html).