Challenges and Lessons Learned

For Micro Air Vehicle

Requirements Development

Final Term Paper

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Course: SYSM 6309

Course Title: Advanced Requirements Engineering

Term: Spring 2012

1. **Abstract**

Micro Air Vehicles (MAVs) have been recently developed by government and military stakeholders in order to accomplish ISR (Intelligence, Surveillance, and Reconnaissance) mission objectives. An MAV is a type of unmanned aerial vehicle (UAV) but is on a scale of smaller than 15 cm. MAV products have also found useful applications in commercial markets and local government. During the concept genesis of MAVs, stakeholders struggled to define mission objectives, which led to incorrect requirements. Technology limitations of small vehicles have also presented challenges in requirements definition. In this paper, we will discuss solutions to Micro Air Vehicle development and lessons learned in defining requirements. Future development of systems will also be discussed.

1. **Introduction**

Micro Air Vehicles, or MAVs, are a class of unmanned aerial vehicle but on a much smaller physical scale. A commonly used definition for MAVs is simply that they are "to be smaller than 15 centimeters in size and may be autonomous” [1]. In general, an unmanned aerial vehicle, such as the Northrop Grumman Global Hawk, is a “remotely piloted, high altitude, long endurance airborne ISR [Intelligence, Surveillance, and Reconnaissance] system” [2]. Many unmanned aerial vehicles, or UAVs, are implemented by the United States military in order to gather visual information of an enemy territory from a remote location. In the case of the Global Hawk system, the goal is to “provide persistent, high-altitude, intelligence collection capabilities […] near real-time […] in all-weather and day/night conditions” [2]. UAV systems such as the Global Hawk are required to operate in extreme environmental conditions and must be designed, tested, and built to meet these operational requirements.

In contrast to Unmanned Aerial Vehicles, Micro Air Vehicles are a relatively new class of UAV that are currently being considered for government and military ISR (Intelligence, Surveillance, and Reconnaissance) applications. One military application is the “observation of hazardous environments inaccessible to ground vehicles” [1]. In this case, the goal of the system is for soldiers on the ground to deploy the MAV in order to collect information about the battlefield without putting themselves in harm’s way. Such a system should be small and lightweight enough to be carried easily by the soldier, such as in a backpack. Honeywell’s MAV, as seen in Figure 2.1 below, can be used to check for roadside bombs and ambushes, and comes with regular day cameras as well as thermal cameras for night vision [3].



Figure 2.1: US Army soldiers using an MAV [3]

MAVs have also gained popularity in commercial and research development applications. In fact, “thousands of hobbyists are taking part in what has become a global do-it-yourself drone subculture” [4]. For instance, two developers in the San Francisco bay area have built a plane similar to a U.S. stealth drone, except miniaturized to a 4 ½ foot wingspan [4]. The hobbyists designed the aircraft to fly autonomously to a specified set of GPS coordinates and altitude. The two men are shown below preparing the aircraft for flight (Figure 2.2). A tiny camera mounted on the vehicle sends live video feed of its aerial view to the user on the ground [4].



Figure 2.2: Hobbyists Mark Harrison and Andreas Oesterer [4]

Real-time video feed technology of MAVs has also piqued the interest of local police and sheriff’s departments who value the aerial imaging capabilities. Some early adopters believe that MAV’s may someday replace the need for helicopters to pursue criminals, since helicopters are expensive and may have a slower reaction time in getting to the scene of the crime. Real Estate agents have begun to use MAVs to capture property footage of homes for sale in order to give internet shoppers a more realistic tour of home sites. Agricultural researchers have expressed the need to equip MAVs with infrared sensors in order to detect dry patches of ground in orchards [4]. In addition, entrepreneurs have sought to apply MAV concepts for innovative service offerings. A start-up company in the San Francisco bay area, named TacoCopter, aims to deliver food via helicopter drone to customers who will make their orders on a smartphone application [5]. Although the FAA currently bans such commercial use of aerial vehicles, the idea is being reserved for future use by the company.

Due to the evolving market for MAVs, the requirements will vary significantly from system to system. Currently, an industry standard definition does not exist for what constitutes a Micro Air Vehicle. The many applications will use different definitions for an MAV, depending on project goals, scenarios, and use cases. In this paper, we will focus on the implementation of MAVs as described by Robert C. Michelson in the paper “Overview of Micro Air Vehicle System Design and Integration Issues”, published in the Encyclopedia of Aerospace Engineering in 2010. This paper will first cover the history and concept genesis of Micro Air Vehicles in Section III. In this section, we will also discuss the evolution of MAV mission goals. In Section IV, a requirements review will be presented along with the challenges associated with defining suitable requirements. In this section, we will also discuss the impact to design considerations of the system. Lastly, in Section V, a recommendation will be given for defining MAV requirements and how to address the challenges in future work.

1. **History and Concept Genesis**

Inventors and designers have long been fascinated with the concept of flight. Many early flight models were based on studies of birds and insects, such as the Leonardo da Vinci flapping wing machine [Overview of MAVs]. Deriving requirements for an engineered system based on biological copycatting is also known as “Bio-Mimicry”. As recent as 1993, the RAND corporation conducted a study that discussed the use of sensor-carrying insects as a concept for a true micro air vehicle [6].

As flight models evolved, it became apparent that bio-mimicry was not sufficient for aerospace design. In the modern age of flight, classical aerodynamic science is used to design conventional aircraft and helicopters. However, the miniaturization of flight vehicles now presents new challenges in requirements engineering and design. As Robert Michelson describes the problem:

“No other air vehicle design space has presented the mix of challenges as that of miniature flight platforms. […] the creators of these aerial robots must address the same physical design constraints which have already been mastered by the world of airborne biology, including low Reynolds number aerodynamics, high energy density, and extreme miniaturization” [6].

Micro Air Vehicles must address the miniaturization challenges since conventional aerodynamic principles do not apply to these scaled-down systems. In the early 1990s, MIT labs conceived of a small airplane that could carry a tiny electro-optical reconnaissance system, although it was never predicted to be capable of actual flight (Figure 3.1). The concept, however, initiated discussion for possible mission goals of a Micro Air Vehicle system. The mission goals are the starting point for defining system requirements.

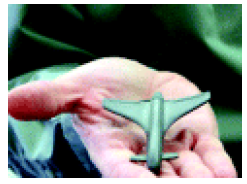


Figure 3.1: MIT Lincoln Labs Concept Model for an MAV [6]

In 1995, when the first DARPA program for Micro Air Vehicles was established, stakeholders had difficulty defining missions, platforms, performance parameters, and the meaning of the term “micro”. Eventually, a Micro Air Vehicle was defined as “being less than 15 cm’ because this represented the juncture at which low Reynolds number effects begin to dominate, and beyond which, integration of energy, propulsion, aerodynamic structures, and intelligence is a necessity” [6]. Although a size requirement was in place, the requirements for volume and shape factor of such a vehicle remained unclear.

The primary stakeholders, including MIT Lincoln Labs, the Georgia Tech Research Institute, Sarcos Labs, and the US Naval Research Laboratory, initially envisioned MAVs to operate in outdoor environments. Specifically, the mission goals were as follows:

“The individual soldiers at the platoon, company, or brigade level would use such vehicles for reconnaissance and surveillance, battle damage assessment, targeting, emplacing sensors, communications relays, or for sensing chemical, nuclear, or biological substances. The 15 cm vehicles would be able to conduct real-time imaging, have ranges of up to 10 km and speeds of up to 30 miles per hour for missions that are 20 minutes to two hours long” [6].

The mission goals described an outdoor “look-over-the-hill” scenario. However, questions still remained regarding whether MAV development was justified for this type of missions. Given the functional requirements for vehicle size, range, speed, and duration of operation, researchers derived functional requirements. For instance, given the size of the vehicle, an assumption was made regarding the maximum size of an antenna that can be supported, which in turn derives the required communication frequency.

Using the mission objectives along with the known requirements, a use-case scenario was created to determine whether the MAV was the appropriate solution. The use-case scenario described the system as needing to reach “an altitude in excess of 500 meters (1640 ft) above the target area. [At this height] the MAV would be neither seen nor heard but neither would a larger air vehicle of perhaps ten times the size” [6]. Given the high altitude required of the MAV, outdoor operation no longer made sense for this system. Indeed, current UAVs could accomplish the same objectives with superior performance in wind and ISR sensing.

With an improved understanding of use-cases, stakeholders changed the mission objectives to fill a market gap for indoor operation, rather than attempt to replace current outdoor technology. This unmet need was realized “after two decades of serious unmanned aerial vehicle (UAV) development […] no assets yet exist that can rapidly and covertly penetrate buildings, tunnels/caves, bunkers, and other enclosures” [6]. Therefore, instead of attempting to replace UAV systems from their market segment, it became a more rational goal to create an entirely new market. In this new market, “MAVs present a new paradigm in reconnaissance where close-in interaction is encouraged rather than a stand-off capability. Key to this behavior is small size, slow flight, and the ability to navigate without GPS” [6]. The small systems could easily penetrate enclosed areas that would be dangerous for soldiers to enter. Also, with an indoor mission, MAVs are not required to sustain the extreme and unpredictable environmental conditions that UAVs are subjected to. A conceptual rendering of such a system is given in Figure 3.2 below.

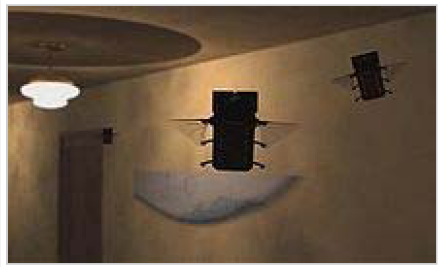


Figure 3.2: A simulation screenshot of a "bumblebee-sized" MAV by the U.S. Air Force in 2008 [1]

In order to meet the challenges of an indoor system, one would assume classical aerodynamics can be scaled down and applied to MAVs. However, at object scales on the order of small birds and insects, classical aerodynamics breaks down because of a low Reynold’s number which “describes the behavior of the air as seemingly much more viscous. Reynold’s number is a dimensionless number that relates inertial forces of an object […] to viscous forces in a fluid” [6]. In this case, the viscous fluid is air.

Conveniently, the low Reynold’s number problem has already been solved by nature throughout millions of years of evolution. Biological mimicry, however, would be poor method for the requirements definition process. Not only are complex biological systems difficult to replicate, but doing so is not necessarily needed to accomplish a usable system. Instead, “biological inspiration” should be implemented by looking “at biological structures in terms of their function, and […] leverage the physical principles involved” [6]. Using this process, engineers can effectively define the system without constraining the solution to match complex biology.

1. **Requirements Review and Challenges**

In this section, we will cover the requirements needed for an exceptional MAV system. Certain key functional requirements must be met in order for an MAV to be a practical solution for indoor ISR applications. Non-functional requirements are also required to define what constitutes a good MAV system capable of mission success. We start by asserting that MAV systems must “be able to fly, be controllable, and have a useful endurance” [6]. This statement has many functional and non-functional requirements associated with it. For example, in order for the vehicle to fly, MAV’s require a high-lift-to-drag ratio due to the limited surface area.

For the system to accomplish lift with limited surface area, the required airfoil shape must be defined. The airfoil shape dictates how the vehicle will behave aerodynamically at low Reynolds numbers. The shape will also help define the type of MAV design, such as a fixed wing, rotary wing, or flapping wing design [6]. Each design type has performance implications depending on their use.

Fixed wing designs are fast flyers (up to 40 mph) and are not suited for indoor use. Rotary-Winged designs, such as miniature helicopters, can “fly slowly and even hover” but have less flight endurance. The decreased flight endurance is due to inefficient power consumption, especially when multiple propellers are used that require increased complexity and weight [6]. A popular implementation of the multiple propeller concept is the “quadrotor”, which uses 4 different propellers, typically each with their own motor and actuators (Figure 4.1 below). Flapping-Wing MAVs, on the other hand, have non-functional qualities such as slower flight and indoor robustness that allow this configuration to have “the greatest survivability and performance indoors” [6]. Based on the characteristics of winged insects, the Flapping-Wing configuration is an example of biological inspiration in requirements definition.



Figure 4.1: Example Quadrotor design type

To accomplish lift, propulsive power is also of key importance. A requirement for high propulsive power implies high energy density of the flight fuel. Unless the fuel can provide, “a useful amount of energy […] onboard the vehicle, [the MAV] will not have the performance or endurance necessary to carry out useful missions [6]. One example requirement for fuel energy density is that the stored fuel shall not exceed 50% of the gross MAV weight. Initially, this requirement posed a problem for designers, since “the average power density for […] battery technology is marginal for small scale flapping-wing flight” [6]. More recently, lithium ion batteries have become the popular choice in MAV systems.

Flight endurance, meaning the length of time the system can operate autonomously, requires sufficient onboard energy. Using biological inspiration, we can study hummingbird energy consumption to realize the birds ingest three times their body weight per day in nectar for energy consumption [6]. This fuel provides immediate energy access to sugars in the food. Although batteries are a long way from this type of chemical energy storage, the concept gives a clear metaphor as a system goal. Possible future solutions for long endurance energy are “chemically fueled motors that do not involve combustion […] and fuel cells that convert chemical fuels directly to electricity” [6]. In addition to fuel density, MAV propulsion systems, such as motors, will be miniaturized in the future.

Flight endurance is also directly correlated with the total weight of the system. In order to minimize system weight without sacrificing strength of materials, certain plastics, such as ABS plastics, can be used because of their stiffness at small scales. The weight requirement is also driven by the size of the onboard electronics. One MAV system requirement calls for “the weight of all onboard electronics [to] be under 10 grams” [6]. Limiting the weight of the electronics, however, will also limit the amount of memory and onboard intelligence of the system, which must be considered as a system trade-off.

Once the system is capable of lift and flight endurance, the MAV must also be controllable. The MAV will be required to have both “inner” and “outer” control loops. The inner-loop is a self-stabilizing loop in order for the system to perform in the presence of air gusts. The outer-loop is the directional control that steers the system on its flight path. The control requirements vary greatly depending on an outdoor or indoor application, since outdoor MAVs must have “enough power, mass, or control surface area […] to fight the extremes of the environment” [6]. Considering our indoor flight mission, the top-level requirement is to be “able to sense and react to avoid disaster in an obstacle-rich environment” [6]. Once an obstacle is detected by the sensors, the system must compute a new trajectory fast enough to maneuver and avoid the collision. The speed at which this process occurs is characterized as non-functional and should be quantified and tested.

In order to accomplish an autonomous MAV indoors, line of sight communication and GPS navigation become impractical for most scenarios. Therefore, navigation is required to be autonomous, possibly accomplished by, “pheromone trials, emitters, a priori architectural knowledge, and self determination” [6]. A fully autonomous system must also have flight controls capable of “automated decision making, obstacle avoidance, target acquisition, target tracking, artificial vision, and interaction with other […] systems” [6]. The possibilities for satisfying these requirements are broad and have many solutions. However, one biologically inspired approach uses honey bee research as a basis for an MAV control technique. Research determined that a honey bee can “observe bilateral flow of objects in their field of view in order to assess their speed and trajectory relative to objects” [Overview of MAVs]. If this type of sensing can be accomplished, an MAV will be one step further in autonomous navigation in obstacle-rich enclosures. Innovative control techniques such as the honey bee example can help create more autonomy for indoor MAVs and also simplify the onboard electronics required. In turn, simplified electronics will also reduce size, weight, and power consumption.

1. **Recommendations and Future Work**

The requirements presented in Section IV are a top-level definition of the most important factors for MAV development. Many more requirements are necessary as system architectures are developed and refined. The important considerations presented are the consequences of indoor versus outdoor operation, and how the indoor scenario traces down to the system requirements. For an indoor MAV system, an autonomous, controllable, lightweight, highly propulsive, high endurance, slow, and robust system is desirable.

In this case, we’ve seen biological inspiration as a useful theme for requirements development. Biological inspiration has been used in the insect-like flapping wing architecture, honey bee-like flight controls, insect-like pheromone tracking, and hummingbird-like energy storage and consumption. MAV development has been a strong example for using biological inspiration rather than bio-mimicry.

One lesson we’ve learned from the history and concept genesis of MAVs is not to fit a pre-defined solution to a problem. Instead, it is more efficient and appropriate to start with a problem statement and goals, and find the solution to the problem afterwards. During concept genesis of the MAV, stakeholders wanted to use an MAV system for primarily outdoor applications. However, upon further review of requirements, they determined that outdoor MAV missions gave no significant advantage over current UAV technology. This was due to the high altitude required, where an MAV would have more difficulty with stabilized controls under the extreme environment. It would also be more difficult for MAVs to accomplish ISR sensing because the system is much smaller and cannot support an adequate payload.

Another lesson learned is that not all technology can be scalable, nor does it make sense to scale certain technologies. The most obvious restriction for MAVs is that classical aerodynamics breaks down at small scales. This is due to a low Reynold’s number, which describes the air as much more viscous for small flight vehicles. This issue led to defining required airfoil shapes and, ultimately, three flight configurations were compared to find the best solution. For an indoor mission, a flapping-wing vehicle proved to have advantages over the fixed-wing and rotary-wing models. Other non-scalable MAV technologies include structural materials, propulsion systems and motors, electronics, GPS capability, and line-of-sight communication.

In future development, MAVs are expected to become more autonomous and versatile, smaller, lighter, and have more endurance. Systems are also expected to be capable of advanced communication in a network that includes other MAVs. Applications of MAV network communication involves complex swarm behavior, guidance, and object tracking. With an evolving marketplace that includes military, government, consumer, and research applications, many different stakeholders are driving requirements and this leads to many system variations. Requirements experts involved with these systems will benefit from the 3 lessons learned for requirements definition. The lessons are: 1) Use biological inspiration rather than bio-mimicry, 2) Start with the problem rather than the solution, and 3) Not all technology is scalable, nor does it make sense. Using lessons learned from previous programs and with continued research and development, MAV developers will continue to produce useful systems that will become more prevalent in the market in the near future.

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