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Development of the Black Widow Micro Air Vehicle

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This paper describes the development of the Black Widow Micro Air Vehicle (MAV) over the past 4 years. An MAV has generally been defined as having a span of less than 6 inches, and a mass of less than 100 grams. The Black Widow is a 6-inch span, fixed-wing aircraft with a color video camera that downlinks live video to the pilot. It flies at 30 mph, with an endurance of 30 minutes, and a maximum communications range of 2 km. The vehicle has an autopilot, which features altitude hold, airspeed hold, heading hold, and yaw damping. The electronic subsystems are among the smallest and lightest in the world, including a 2-gram camera, a 2-gram video downlink transmitter, and a 5-gram fully proportional radio control system with 0.5-gram actuators. A Multidisciplinary Design Optimization methodology with a genetic algorithm was used to integrate the MAV subsystems and optimize the vehicle for maximum endurance. Some of the potential missions for MAVs are visual reconnaissance, situational awareness, damage assessment, surveillance, biological or chemical agent sensing, and communications relay. In addition to these military missions, there are several commercial applications, such as search and rescue, border patrol, air sampling, police surveillance, and field research.

Introduction

The first feasibility study for Micro Air Vehicles (MAVs) was performed by the RAND Corporation in 1993.[1] The authors indicated that the development of insect-size flying and crawling systems could help give the US a significant military advantage in the coming years. During the following two years, a more detailed study was performed at Lincoln Laboratory.[2] This study resulted in a DARPA workshop on MAVs in 1995. In the fall of 1996, DARPA funded further MAV studies under the Small Business Innovation Research (SBIR) program. AeroVironment performed a Phase I study, which concluded that a six-inch MAV was feasible. In the spring of 1998, AeroVironment was awarded a Phase II SBIR contract, which resulted in the current Black Widow MAV configuration.

Several universities have also been involved in MAV research. Competitions have been held since 1997 at the University of Florida and Arizona State University. The goals of the competitions have been to observe a target located 600 m from the launch site and to keep a two-ounce payload aloft for at least 2 minutes.

Early Prototypes

In the early stages of the Black Widow MAV program, several prototypes were built to explore the 6-inch aircraft design space, which was largely unknown at the time. About twenty balsa wood gliders with different wing configurations were built, and simple tests were performed to determine the lift-to-drag ratios. These tests showed that the disc configuration had some promise, so a powered version was built next. The powered 6-inch disc performed a 9-second flight in the spring of 1996. The endurance was gradually increased using the disc configuration, culminating in a 16-minute flight using lithium batteries in November of 1997. This MAV weighed 40 grams, it was manually controlled by elevons, and it did not carry a payload (Figure 1).

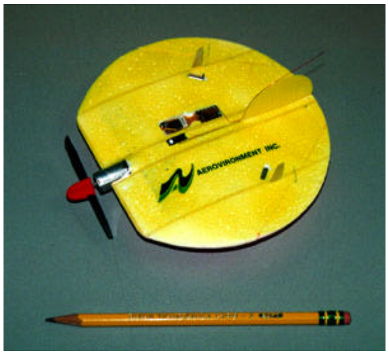

Figure 1: Early MAV prototype

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Multidisciplinary Design Optimization

The early prototypes demonstrated that a 6-inch aircraft was feasible. However, the MAV still required a video camera and an advanced control system that would allow operation by an unskilled operator. Since the prototype MAVs were clearly not capable of handling the extra weight and power of these additional systems, a more rigorous design approach was required to continue evolving the system toward maturity.

For this reason, a Multidisciplinary Design Optimization (MDO) methodology was developed in the summer of 1998 to maximize the performance of the MAVs. The goal of the MDO methodology was to create a computer-simulated environment in which the optimum MAV configuration could evolve. The simulated environment consists of physics-based models of the key aspects of the MAV design space, as shown in Table 1. The design variables used for the first generation MAV optimization study are shown in Table 2. The objective function was to maximize the endurance of the MAV. In the MAV MDO code, the optimization is performed by a genetic algorithm.

Table 1: Subsystem model descriptions

Subsystem Model	Description
Vehicle aerodynamics	Lifting line theory for induced drag, Blasius skin friction formulas for friction drag, Hoerner equations for interference drag, and equivalent parasite areas for protuberance drag
Propeller aerodynamics	Minimum induced loss methodology
Motor performance	Analytic motor model with coefficients adjusted to match experimental data for each motor
Battery performance	Curve fits of battery endurance vs. power draw based on experimental data
Weight buildup	Mass budget of all fixed components, and simple weight equations for variable masses

Table 2: MAV design variables

Design Variable	Range/Options
Battery type	2
Motor type	9
Gearbox type	4
Motor power draw	1-5 W
Propeller diameter	2-4 in
Wing tip chord	0-6 in
Loiter velocity	20-40 mph

The vehicle aerodynamics model was validated by performing wind tunnel tests on a variety of wing configurations. This allowed validation of the induced drag and friction drag parts of the code. The protuberance and interference drag components were then added individually.

The propeller aerodynamics model was validated by testing four different propellers in the wind tunnel over a range of velocities, airspeeds, and power levels. Both direct drive and geared props were tested.

The motor model was validated by using the Solver in Excel to adjust the coefficients in the analytic motor model equations to minimize the error between the model predictions and experimental performance measurements over a range of shaft loads and power levels. Most of the motor models show less than 5% error from the experimental data.

The battery model is simply a curve fit through experimental discharge data at different power loads, so no validation was necessary.

Most of the early MAV prototype vehicles were flown with direct drive propellers. A few geared propeller configurations were built, but they had marginal performance. However, it was felt that the geared prop concept still had enough potential to merit further study for the first generation of the Black Widow. Therefore two optimum configurations—a direct drive prop and a geared prop—were created as candidates for the final configuration.

Even though the entire vehicle was optimized for each of the drivetrain types, the tip chords of both configurations were roughly the same, and the loiter velocities were roughly the same. The optimizer also selected the same battery and the same motor for both configurations. Therefore these parameters were all frozen to the same values, to allow a normalized comparison between the direct drive and geared propulsion systems. Table 3 shows the wing shape parameters, and Table 4 shows a comparison of the direct drive and geared propulsion systems.

Table 3: Wing shape parameters (common to both direct drive and geared prop designs)

Wing span	6.0 in
Wing centerline chord	5.4 in
Chord at spanwise breakpoint	5.4 in
Wing tip chord (in)	3.9 in
Spanwise position of breakpoint	1.5 in
Wing thickness/chord ratio	8.4%

Table 4: Propulsion system parameters for direct drive and geared propeller configurations

	Geared Prop (4:1)	Direct Drive Prop
Required thrust	9.9 g	9.4 g
Propeller diameter	3.81 in	2.67 in
Propeller RPM	5,365	22,400
Propeller efficiency	80%	68%
Gearbox efficiency	81%	N/A
Motor RPM	21,460	22,400
Motor efficiency	62%	63%
Total propulsion efficiency	40%	43%
Power draw from batteries	4.65 W	4.35 W
Battery endurance	30.2 min	33.4 min

The optimization code predicts that the endurance of the geared prop configuration is 30.2 minutes, while the direct drive prop configuration has an endurance of 33.4 minutes. The direct drive prop configuration achieves about 10% greater endurance than the geared prop configuration. This is mainly due to the efficiency loss in the gearbox, the added weight of the gearbox, and a larger and heavier propeller.

In order to increase our confidence in this prediction, both propulsion systems were tested in the AeroVironment wind tunnel over a range of operating conditions. Figure 2 shows the propeller efficiency, motor/gearbox efficiency, and the combined motor/gearbox/propeller efficiency vs. thrust at a freestream velocity of 25 MPH for the geared propeller configuration. The vehicle drag at 25 MPH (the optimum loiter velocity) is 9.9 g for the geared prop configuration. Therefore 9.9 g of thrust is required for level flight. Notice that the slopes of the propeller and motor/gearbox efficiency curves are in opposite directions near 10 g of thrust. Therefore the best total propulsion system efficiency is obtained by making the optimum tradeoff between the two efficiencies. Note that the optimizer did this automatically, achieving a total propulsion system efficiency of 40%. Figure 2 shows the experimental data, which agrees well with the predicted performance shown in Table 4.

Figure 3 shows the propeller, motor, and combined propeller/motor efficiencies vs. thrust at 25 MPH for the direct drive prop. Since the direct drive configuration is slightly lighter than the geared prop configuration, it has less induced drag, and the required thrust is 9.4 g. Notice that the propeller and motor efficiencies both decrease with increasing thrust at the design point of 9.4 g. Therefore the combined propulsion system efficiency does not have an unconstrained maximum at the design point like the geared prop test results. The maximum attainable efficiency is constrained by the required thrust to be 43%. The propeller wind tunnel tests have increased our confidence in the validity of the optimization code, and they have shown that the direct drive propeller configuration outperforms the geared prop configuration. Therefore we chose to use a direct drive prop for the first generation Black Widow configuration.

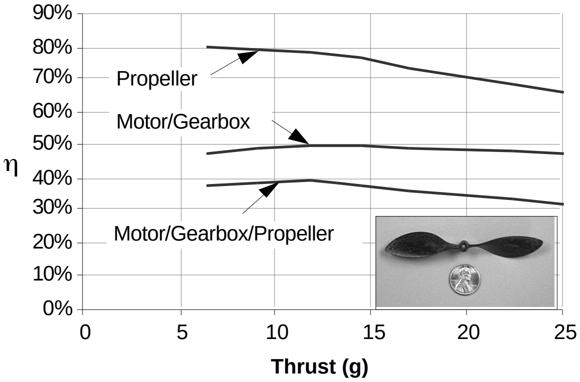

Figure 2: Propeller, motor/gearbox, and combined efficiencies vs. thrust at 25 MPH for geared prop

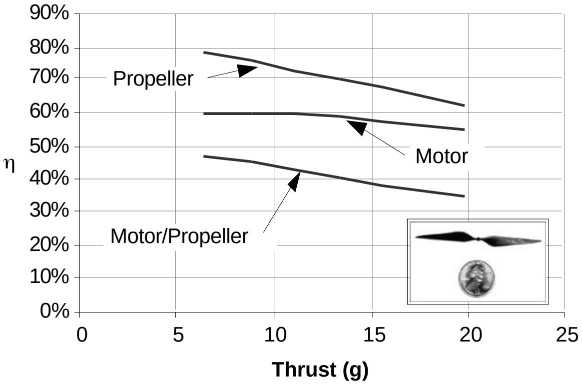

Figure 3: Prop, motor, and combined efficiencies vs. thrust at 25 MPH for direct drive prop

Table 5 presents a performance summary for the first generation Black Widow configuration. Figure 4 shows the mass breakdown.

Table 5: Performance summary for the first generation Black Widow MAV

Total mass	56.5 g
Loiter drag	9.4 g
Lift/drag ratio	6.0
Loiter velocity	25 mph
Loiter lift coefficient	0.42
Loiter throttle setting	70%
Endurance	33.4 min

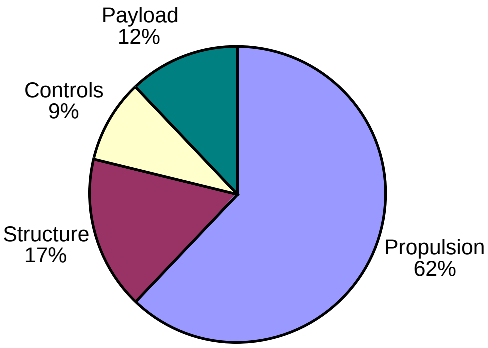

Figure 4: Mass breakdown for the first generation Black Widow configuration

After arriving at the optimum configuration, a brief sensitivity analysis was performed. This analysis showed that an additional 1 gram of drag would decrease the endurance by 3 minutes, and an additional 1 gram of mass would decrease the endurance by 30 seconds.

The first generation MAV configuration performed a 22-minute flight with a black and white video camera on March 3, 1999. This vehicle weighed 56 grams, and had a cruise speed of 25 mph. The next step was to add color video and increase the endurance to our goal of 30 minutes. In the summer of 1999, we performed another design iteration, and further refined the Black Widow design. The final vehicle is shown in Figure 5. The vehicle is controlled by a rudder on the central fin, and a small elevator in the middle of the trailing edge. The pitot-static tube can be seen extending forward from the right wing tip.

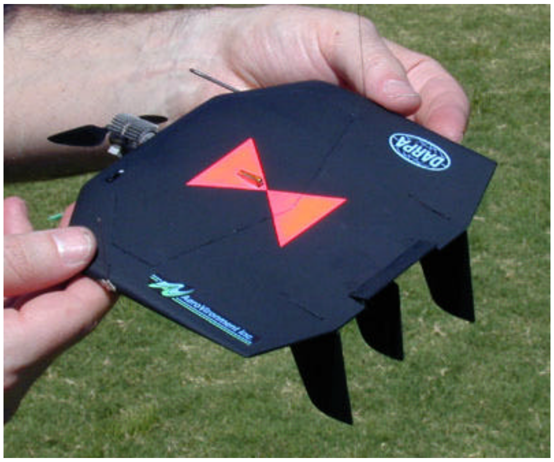

Figure 5: Final Black Widow MAV configuration

Energy Storage

In the beginning of the MAV program, we evaluated a wide range of power sources, including internal combustion engines, fuel cells, micro turbines, and solar power, but the best source of energy among currently available technologies turned out to be modern lithium batteries. Fossil fuels have a much higher energy density than batteries, but the currently available small internal combustion engines are extremely inefficient, difficult to throttle, and generally quite unreliable. Small fuel cell technology looks promising, but it is not here yet. Microturbines also look promising, but they may take even longer to mature. Solar cells cannot supply enough energy to sustain level flight, but they could be used to recharge the batteries while the MAV is parked somewhere.

Batteries and electric motors are extremely reliable, inexpensive, and quiet. However there are tradeoffs among different battery chemistries. Nickel-Cadmium (NiCd) and Nickel-Metal-Hydride (NiMH) batteries have very high power densities, but very low energy densities. Lithium (Li) batteries are generally designed to have high energy densities, but relatively low power densities. Also, NiCd and NiMH batteries are rechargeable, while most lithium batteries are not. We chose to use NiCd and NiMH batteries for flight testing, and lithium batteries for demonstration flights.

As with any aircraft, the energy source is a primary design driver. Therefore it is critical to have quantitative data for many different batteries in order to select the best battery for the vehicle. During the MAV program, we characterized a variety of small batteries using discharge tests over a range of temperatures. We reduced this data to a series of curve fits, and we used the curve fits in the MAV optimization code.

Motors

Throughout the MAV program, we tested and evaluated several electric motor candidates. We built a dynamometer specifically for small motors, and we tested each motor over a wide range of operating conditions. The motor test data was used to create an analytic math model of each motor. These motor models were then integrated into the MDO code.

The dynamometer tests showed that efficiencies as high as 70% can be achieved with small motors. The trends are that larger motors have higher efficiency to power ratios, and higher voltage motors have higher efficiency to power ratios. Unfortunately the motor voltage is limited by the battery supply voltage unless a power converter is used.

Micro-Propeller Design

The early MAV prototypes used plastic propellers developed for small model airplanes. Some of these propellers were modified by cutting and sanding commercially available props. Since the propeller performance is critical to the success of the MAV, we developed a propeller design methodology which allows us to significantly increase the efficiency of small propellers.

The nominal mission profile for the Black Widow is to climb to about 200 ft above ground level, and cruise around at the optimum loiter velocity gathering video data. Therefore at least 90% of the flight occurs at a single flight condition. This greatly simplifies the propeller optimization, since the off-design conditions do not strongly affect the overall performance. It also allowed us to use the minimum induced loss propeller design methodology to optimize the twist and chord distribution for the loiter flight condition. The prop diameter was optimized by the genetic algorithm along with the other top-level vehicle design variables.

The propeller shown in Figure 6 was optimized for a 4:1 gearbox and a 7-gram DC motor. The pitch is 6.04 inches, and the diameter is 3.81 inches.

Figure 6: Micro-propeller designed for 4:1 gearbox

A 3-dimensional model of the propeller geometry was created using the SolidWorks solid modeling software. Stereolithography models of the upper and lower mold halves were then created from the virtual solid model. Figures 7 and 8 show the prop mold geometry. The propeller was fabricated from unidirectional and woven carbon-fiber composites.

To validate the propeller design code, a series of tests were performed in the AeroVironment wind tunnel. The wind tunnel is an open-circuit, suction design with a test section that is 20 inches wide, 20 inches high, and 40 inches long. The tunnel is capable of producing velocities between 5 and 80 mph in the test section. The torque and thrust were measured using the balance shown in Figure 9. This balance was constructed using three load cells from commercially available scales. The load cells have a 0.1-g accuracy, and they are insensitive to offset loads and moments.

Figure 7: Upper half of propeller mold

Figure 8: Lower half of propeller mold

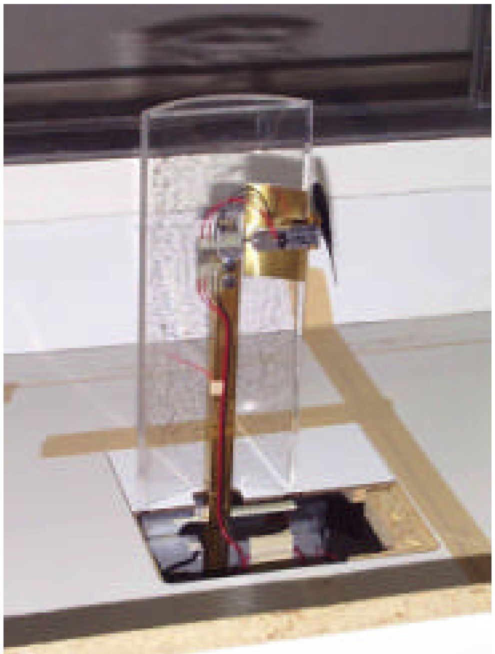

Figure 9: Balance for prop performance tests

Figure 10 shows the thrust vs. RPM and freestream velocity for the prop. The plot shows excellent agreement between the experimental data and the code predictions. The propeller was designed to produce 10 g of thrust at 25 MPH and 5,250 RPM.

Figure 11 shows the propeller efficiency vs. RPM and velocity for the prop. The best measured efficiency was 83%, while the code predicted a peak efficiency of 82%. The propeller actually operates at 78% efficiency, even though the peak efficiency at 25 MPH is 81%. Since the motor efficiency is higher at higher speeds, a slight sacrifice in propeller efficiency increased the efficiency of the total propulsion system. Also note that the peak efficiency increases with increasing freestream velocity due to higher blade Reynolds numbers.

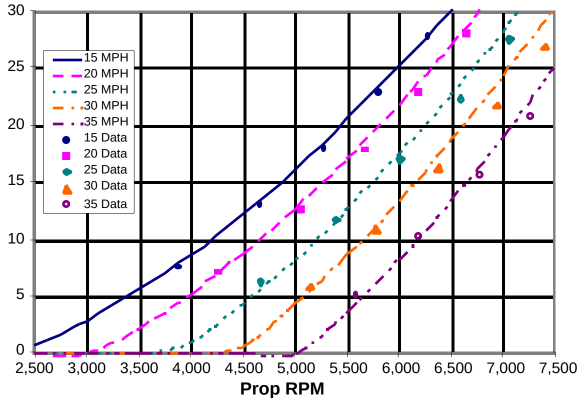

Figure 10: Thrust vs. RPM and freestream velocity for 3.81-inch diameter propeller

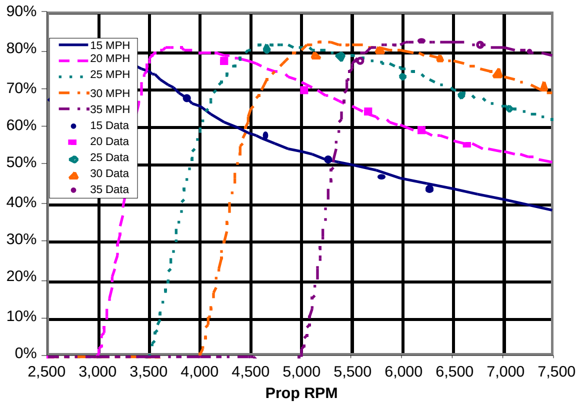

Figure 11: Efficiency vs. RPM and freestream velocity for 3.81-inch diameter propeller

Airframe Structural Design

The structural design of an MAV presents several unique challenges. Because of the square-cube law, the inertial loads induced on an MAV during accelerations and decelerations (such as takeoff and landing) are quite small relative to larger aircraft. During a typical landing, the MAV flies into the ground at a shallow angle and survives a few bounces with no damage. In fact, the worst case design loads for many parts of the structure are the handling loads imposed by people.

The first generation Black Widow design used a solid foam wing structure with some internal reinforcements in high-stress areas. The wing structure consists of the basic wing, the internal rigid structure, and the vertical fin assembly, as shown in Figure 12.

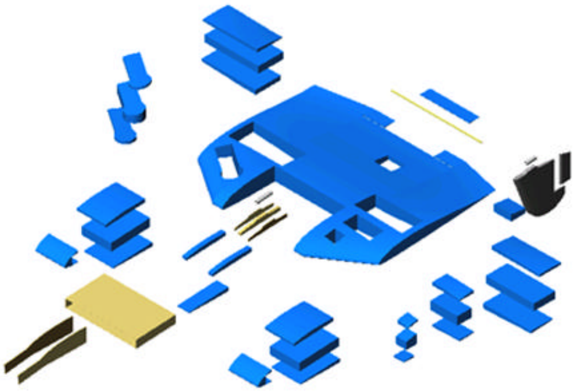

Figure 12: Solid foam wing structure

The wings are fabricated from expanded polystyrene (EPS) foam. The foam has many desirable qualities, including ease of shaping, light weight, strength, and ease of bonding.

The main pieces in Figure 12 are shaped by cutting using a hot wire tool. The ends of the wire are moved by CNC-controlled stepper motors, such that precision cuts can be made from CAD drawings.

A cavity is cut from the leading edge of the center wing section. This is the area where the internal rigid structure is embedded. The internal rigid structure is designed to hold the most massive parts of the MAV, (batteries and motor) together, and tie into the high load points of the MAV, such as the launch lug. The rigid structure is mainly fabricated from fiberglass sheet.

The vertical fin assembly is hand fabricated from balsa wood. The rudder is also made of balsa wood and is hinged with Kevlar cloth.

Avionics

One of the objectives for the Black Widow MAV is to achieve autonomous flight so that the vehicle can be easily operated by an unskilled operator. The first step toward autonomous flight is to sense the state of the vehicle and pass the data to the flight computer. For this reason, the Black Widow has a two-axis magnetometer to sense compass heading. A pitot-static tube is connected to an absolute pressure sensor to sense altitude and a differential pressure sensor to sense dynamic pressure. The vehicle also uses a piezoelectric gyro to sense the turn rate.

The MAV must also receive commands from the ground station, and translate the commands into control surface movements and throttle changes. This requires a command uplink receiver, a flight computer, and control actuators. The uplink receiver has a mass of 2 grams, and is about the size of two postage stamps. It operates at 433 MHz. The aircraft uses two microprocessors to perform onboard computations. The rudder and elevator control surfaces are moved with custom-developed 0.5-gram actuators.

Video Camera Payload

The Black Widow MAV was developed as a platform to deliver live color video images in real time to an observer on the ground. The video payload evolved from a current off-the-shelf (COTS) video transmitter, and a modified COTS black and white CMOS camera, to a custom video transmitter and a custom color CMOS camera, as shown in Figure 13.

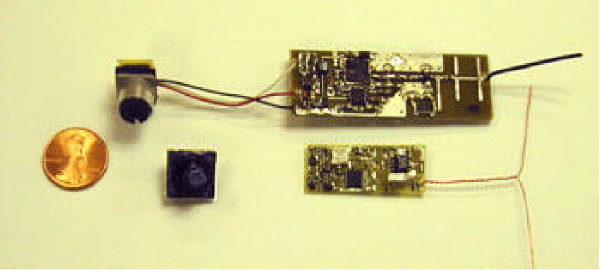

Figure 13: Black & white camera, COTS transmitter (top); custom color camera, custom transmitter (bottom)

There are a wide variety of micro video cameras on the market today. The challenge for an MAV is to find a good balance of high image quality, low weight, low power, and small size. We found a good compromise with the CMOS video cameras. Table 6 shows the specifications for the CMOS cameras used on the Black Widow.

To get the video from the onboard camera to the ground, we used a radio frequency (RF) transmitter operating at 2.4 GHz. The transmitter takes the analog video stream as an input, modulates it using frequency modulation (FM), and outputs it as a RF signal. 2.4 GHz was used because commercial video receivers and antennas are readily available. The first generation COTS video transmitter had moderate performance because of low power conversion efficiency in the RF amplifier section. For the final MAV system, an improved transmitter with higher output power, smaller size, and lighter weight was developed.

Table 6: CMOS video camera specifications

	Black & White	Color
Mass (g)	2.2	1.7
Power (mW)	50	150
Resolution (pixels)	320 x 240	510 x 488

Table 7: Video downlink transmitter specifications

	First Generation	Final
Mass (g)	3.3	1.4
Power Input (mW)	550	550
Power Output (mW)	50	100
Frequency (GHz)	2.4	2.4

Stability and Control

The small size of an MAV creates several unique stability and control challenges. Since the mass moment of inertia scales as the fifth power of the characteristic dimension, small vehicles tend to have high natural frequencies of rotational oscillation. Obtaining a stable video image requires an actively stabilized camera mount or an actively stabilized aircraft. Therefore high oscillation frequencies require a control system with fast processors and fast actuators to stabilize the camera or the entire MAV. Since wing loading decreases with decreasing size, small air vehicles are quite susceptible to gusts. Even small birds (with highly evolved active control systems) have trouble maintaining steady flight in extremely turbulent conditions.

The main stability augmentation system used on the MAV is a yaw damper. Many of the early prototype MAVs showed a 3 Hz Dutch roll oscillation. The addition of more vertical tails and the yaw damper significantly increased the damping ratio. The MAV has three autopilot modes: dynamic pressure hold, altitude hold, and heading hold. More autopilot modes may be added in the future as the system becomes more advanced, and as new sensors, such as a GPS receiver, are added. We also developed a data logging system which can sample 16 channels of data at 20 Hz for 4 minutes. This was used to evaluate and refine the control system dynamics.

Performance

On August 10, 2000 the Black Widow MAV performed a flight which most likely established several world records for the MAV class of aircraft. Table 8 summarizes the performance on this flight. The pilot flew about 90% of the flight "heads-down," which means he was looking only at the video image and downlinked sensor data from the MAV.

Table 8: Performance summary for the Black Widow flight on August 10, 2000

Endurance	30 min
Maximum Range	1.8 km
Maximum Altitude	769 ft
Mass	80 g

Since the Black Widow uses an electric propulsion system, it is extremely difficult to observe in the air. It cannot be heard above ambient noise at 100 ft, and unless you're specifically looking for a 6-inch square black dot in the sky directly overhead, you can't see it. It looks more like a bird than an airplane. In fact, we have seen sparrows and seagulls flocking around the MAV several times.

Figure 14: Black Widow ground control unit and cassette launcher shown deployed (above) and stowed (below)

Ground Control Unit

In addition to the MAV itself, a fully functional MAV system requires a user-friendly, rugged, and compact ground control unit (GCU). The Black Widow GCU evolved through three stages to reach its final form. the first generation GCU was a collection of off-the-shelf equipment which was quite bulky, and had to be assembled at the field. The second generation GCU was a 15-lb briefcase that contained the MAV, a pneumatic launcher, a removable pilot's control unit with a 4-inch LCD display for the downlinked video, and an automatic tracking antenna. The final GCU (Figure 14) is built around a Pelican case, which is extremely rugged, compact, and waterproof. The MAV is stored in a separate cassette box, which also serves as the launcher. To fly an MAV, the user simply connects the GCU to the launch cassette with a cord, aims the box to the sky, and presses the launch button on the pilot's controller.

Conclusions

The Black Widow MAV program has been quite successful in proving that a 6-inch aircraft is not only feasible, but that it can perform useful missions that were previously deemed impossible. Additionally, the Micro Air Vehicle concept has opened the doors to many new avenues of research in the fields of aerodynamics, propulsion, stability and control, multidisciplinary design optimization, microelectronics, and artificial intelligence. Some of the specific conclusions resulting from the Black Widow development are:

- A direct drive propulsion system appears to be more efficient than a geared propulsion system at the MAV scale.
- Propeller efficiencies of 80% or greater are possible at the MAV scale.
- Motor efficiencies of 70% or greater are possible at the MAV scale.
- An electric propulsion system appears to be the simplest, cheapest, stealthiest, and most reliable option with today's technology.
- The Multidisciplinary Design Optimization methodology is essential to maximize the efficiency of the entire MAV propulsion system.
- The propulsion system efficiency is the key parameter in maximizing the endurance of an MAV.

- Since the structural weight of an MAV does not vary significantly with configuration variations, the structures subsystem is weakly coupled to the other aircraft subsystems at the MAV scale.
- It is possible to build a basic avionics suite with data logging capability at the MAV scale.
- A color video camera with downlink transmitter can be built with a mass of about 3 grams using current technology.
- A 6-inch span, electric MAV is capable of downlinking live color video from a range of 1.8 km, with an endurance of 30 minutes, and a vehicle mass of 80 grams.

Acknowledgments

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References

1 Hundley, Richard O., and Gritton, Eugene C., "Future Technology-Driven Revolutions in Military Operations," RAND Corporation, Document No. DB-110-ARPA, 1994.

2 Davis, W.R., "Micro UAV," Presentation to 23rd AUVSI Symposium, July 15-19, 1996.