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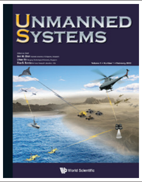

icarusLabs: An Adventure in Crowdsourcing

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From September 2011 through May 2012, icarusLabs competed in the UAVForge Competition, sponsored by the United States Defense Advanced Research Projects Agency (DARPA). The objective of the competition was to design and build a small unmanned aerial vehicle (UAV) that could complete a local surveillance mission. A unique feature of the competition was an experimental crowdsourcing model, in which competing teams were able to provide technical feedback to each other as part of the design process. The icarusLabs team's solution to the challenge combined a tricopter and blended wing body aircraft into a single hybrid airframe. This paper presents the rationale and theory behind the design as well as the lessons learned from the technical and logistical challenges faced. In addition, the authors reflect on the crowdsourcing aspect of the challenge from a competitor's perspective. Overall, incentives for individual teams' success directly conflicted with the essence of crowdsourcing, but the competition was successful at stimulating interest to fill a void in current UAV solutions, bringing together passionate individuals from the global unmanned systems community, and generating a broad range of novel approaches to address the presented challenges.

Keywords: Crowdsourcing; unmanned aerial vehicle; icarusLabs.

1. Introduction

In September 2011, the United States Defense Advanced Research Projects Agency (DARPA) organized the UAVForge Competition,[1] designed to elicit innovative ideas from the international community for the next generation of unmanned systems. Although unmanned systems are becoming increasingly prevalent on the global stage, there is a growing need for small systems that can inexpensively and reliably perform tasks without the need for complex infrastructure or multiple, highly-trained operators. DARPA put forth a challenge to create a small, unmanned aerial vehicle (UAV) platform to complete a short range intelligence, surveillance and reconnaissance (ISR) mission. As a unique twist, the UAVForge Competition introduced a crowdsourcing model, calling for collaboration between members of the international unmanned systems community to solve the challenge.

This paper describes the competition from the perspective of the icarusLabs team,[2] which consisted of 11 engineers based in the northeastern United States. Section 2 describes the competition structure and stated mission objective set forth by DARPA. Section 3 discusses the icarusLabs team's solution and design justifications. Sections 4 and 5 discuss lessons learned throughout this competition, both internal to the team and regarding the competition as a whole.

2. UAVForge Competition

The UAVForge Competition was organized by DARPA as an attempt to crowdsource the development of a UAV system on an accelerated timescale. In this section, a brief summary of the competition is provided as background for discussion of icarusLabs' final design decisions and implementation. The final icarusLabs solution was designed to complete

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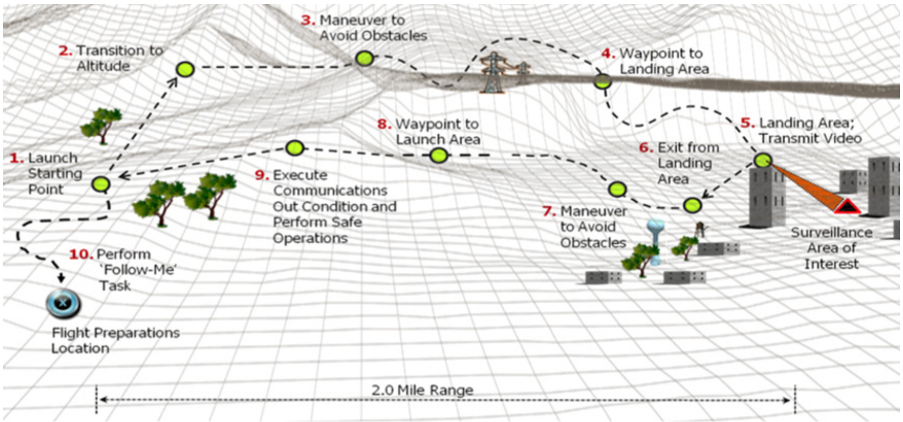

Fig. 1. UAVForge competition course.[1]

DARPA's mission profile, described in Sec. 2.1. The competition structure is outlined in Sec. 2.2.

2.1. *Mission profile*

The design objective of the UAVForge Competition sought to address a relevant problem for current UAV systems: the lack of short range, low-cost surveillance vehicles. The requirements called for a vertical takeoff and landing (VTOL) capable UAV to complete a local surveillance mission. The operational requirements were to fly 2.0 miles via global positioning system (GPS) waypoints to a target location, navigate around obstacles, and relay three hours of real-time, actionable surveillance video of a target while remaining undetected by observers on the ground. A diagram of the conceptual concept of operations published by UAVForge is shown in Fig. 1. No specific details were given in advance about the terrain, but non-line-of-sight (NLOS) communications were required. The entire flight system needed to be as user-friendly as possible, ideally requiring minimal piloting skills by the operator on the ground. In addition, the system needed to be operated and carried by a single person and had to fit into a standard issue military rucksack. Beyond these baseline requirements, additional points would be awarded to vehicles that exhibited advanced capabilities, such as autonomous flight, acoustic signature reduction, or the ability to follow a vehicle.

2.2. *Competition structure*

The UAVForge competition was composed of three phases. Phase I included three video submissions demonstrating the teams' progress in system development and testing. Phase II consisted of a live demonstration where selected finalists competed in a Competition Fly-Off. The winner of the Fly-Off, as selected by DARPA, would progress on to Phase III and complete an Operational Exercise consisting of actual fielded use of the developed UAV. This final phase of the competition would be a collaboration between the winning team and a DARPA-selected United States-based manufacturer, Northwest UAV, to produce 15 units of the winning design for field use.

The crowdsourcing occurred exclusively in Phase I, in which teams had to complete the following three milestones:

(1) Submit a concept video (by October 2011),
(2) Submit a video demonstrating proof of flight (by December 2011),
(3) Perform a live video demonstration (by March 2012).

Since Milestone 3 was the only point of elimination in Phase I, new teams could join the competition at any time during that phase. For each milestone, teams uploaded their videos to the UAVForge website where they were made available for viewing by other teams and the general public. During the feedback portion of each milestone, all registered users on the website were encouraged to rate and provide feedback to each other regardless of team affiliation. At each milestone, crowd rating was factored into each team's score. Forty-three teams submitted videos for Milestone 3. Of these, DARPA selected 12 teams to continue on to Phase II based on their performance at each of the milestones and on supplementary material provided to the competition organizers. These top 12 teams were invited to participate in the Competition Fly-Off, which took place in May 2012 at Fort Stewart, Georgia, USA, and consisted of a demonstration of a specified mission profile. Each design was scored based on its ability to complete the Baseline Objectives set forth at the beginning of Phase I, and the winning design had to achieve every baseline objective in order to proceed to the next phase. In addition, bonus points were awarded for completing advanced behaviors. The winner of the Fly-Off was to receive a grand prize of USD$100,000, along with a contract to work with a designated manufacturer to provide 15 units to DARPA to complete Phase III.

3. The icarusLabs Solution

This section describes how the icarusLabs team approached the solution for the UAVForge Competition. Section 3.1 describes the team's membership and outlines how the team created the infrastructure necessary for success in this competition. Section 3.2 describes the team's novel hybrid air vehicle concept developed for the competition. Section 3.3 discusses the design analyses and processes that iteratively led to the final solution.

3.1. *The team*

The icarusLabs team was composed of 11 aerospace, electrical, and mechanical engineers, with specialties in controls and flight dynamics, manufacturing, systems integration, autonomy, and vehicle design. With most of the members having recently completed college, the competition provided an excellent challenge and opportunity to put skills into practice. The members divided tasks among subsystem teams, but each member assumed multiple roles based on expertise and interest. Spread over five states spanning 400 miles, the team members needed to create a system to allow for rapid prototyping and collaboration between members. Collaboration among the team was accomplished through the use of several freely available collaboration tools. Redmine[3] project management software allowed for centralized documentation and bug tracking. Additionally, a Subversion[4] version control system allowed for collaborative development of the software. The team also made extensive use of the Google infrastructure, including Google Drive and Groups,[5] through which information regarding the project could be dispersed quickly in an organized fashion, as well as Google Hangout, through which the team held regular video meetings. Tools such as Etherpad[6] allowed for collaborative editing of documents. Design decisions, along with manufacturing and safety procedures, were documented in detail along the way to facilitate efficient progress and organization.

3.2. *The solution*

To approach the problem, the icarusLabs team prioritized achieving DARPA's baseline objectives but also aimed to

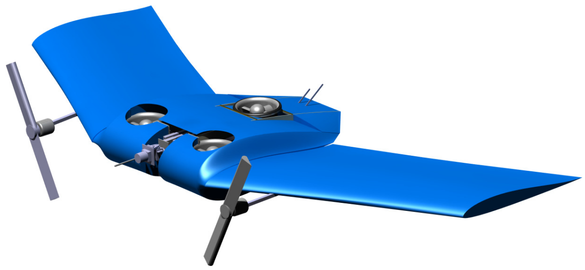

Fig. 2. icarusLabs' final vehicle design for the UAVForge competition.

complete many of the advanced behaviors. The final design, shown in Fig. 2, is a dual-motor blended-wing-body design that incorporates three electric ducted fans (EDFs) in a tricopter configuration. This hybrid design was intended to provide VTOL capabilities coupled with the range of a traditional fixed-wing UAV. The airframe, composed of carbon fiber and expanded polypropylene (EPP) foam, was lightweight and resilient, capable of surviving rough landings and multiple falls from approximately 10 feet. A gimbaled camera provided a forward-facing view during flight and was mounted on an extendable arm for more effective surveillance when landed. The vehicle itself could be disassembled into three modular sections in order to meet the packing requirements and fit in a rucksack.

The operator controlled the vehicle via a laptop-based ground station and had access to both high-level waypoint control as well as remote-control piloting as desired. Control of the vehicle was designed to be easy and intuitive and was partially autonomous, including automatic takeoff and assisted transition from hovering to forward flight. A laptop displayed telemetry and status information from the vehicle along with the video feed for surveillance. The vehicle was equipped with an automatic loss-of-communications behavior, wherein the vehicle would return to the launch point if the communications link was lost. The design also included vision algorithms for autonomous obstacle avoidance and target tracking, although this feature was still in progress at the time of the Fly-Off.

During system design, the team emphasized ease of operation and low-cost manufacturing. Vehicle components were selected from available commercial-off-the-shelf (COTS) parts to minimize development and manufacturing costs. The airframe's parts, designed to be modular and durable such that they would be simple and intuitive to assemble and replace, were the only components manufactured in-house. The team selected an open-source autopilot with autonomous GPS waypoint tracking and many other features. While quite capable in its own right, the autopilot's open source code allowed the team to design and implement a novel controller for the custom airframe, and to integrate a more extensive computing architecture for advanced capabilities, such as autonomous obstacle avoidance.

This novel solution showed promise in the early phases of the competition, performing well in the first three competition milestones. A strong showing in Milestone 3 earned the team an invitation to the Fly-Off Competition as one of the top 12 teams. However, due to unforeseen complexities of the design, successful transition between the hovering and forward flight modes did not converge as planned for the final vehicle iteration, despite an extended testing schedule. Between a slipping schedule and last-minute system failures, the team ultimately chose to decline the invitation to the Fly-Off.

3.3. *The design process*

The design process began with a discussion of vehicle configurations and an assessment of how well each configuration would perform in the various phases of the mission profile. The configurations considered for the vehicle were a traditional fixed-wing, flying wing, tail-sitter, tilt-rotor, and multi-rotor. The team evaluated the feasibility of each conceptual design using fundamental aerodynamic, propulsion, and systems configurations, determining the following:

- A traditional fixed-wing configuration, even though most efficient in forward flight, would not be able to accomplish the required VTOL maneuvers.
- A flying wing design would have the same maneuvering limitations as a traditional fixed wing vehicle, with added aerodynamic and design complexity.
- A tail-sitter configuration would be visible and susceptible to wind gusts during surveillance while perched on a roof.
- A tilt-rotor configuration added complexities that would complicate the manufacturing process and increase the number of single point failures.
- A multi-rotor design would likely consume a large portion of available power transporting the surveillance equipment to the active site.

After the initial trade-off, the team selected an innovative approach: creating a hybrid vehicle that would combine the benefits of a fixed wing aircraft with the VTOL capabilities of a rotorcraft.

By combining a fixed-wing configuration with lift fans, the vehicle would be able to operate in two distinct modes, performing efficiently on the transit to and from the surveillance site, while also allowing for precision VTOL landings. This decision to combine two conventional configurations into a single vehicle remained throughout the entire competition despite other significant changes to the airframe. The evolution of the icarusLabs' vehicle is displayed in Fig. 3 and the design specifications are shown in Table 1.

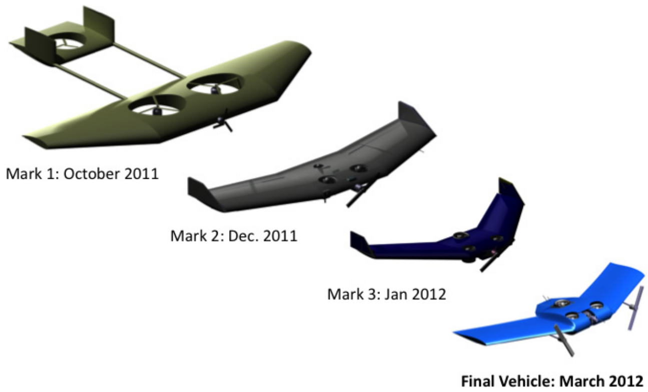

Fig. 3. Design evolution of icarusLabs' vehicle.

Table 1. Design specifications for each vehicle iteration.

Vehicle Iteration	Mark 1	Mark 2	Mark 3	Mark 4
Gross Weight [kg]	4.5	4.5	2.5	2.5
Wing Span [m]	1.6	1.4	1.0	1.2
Cruise Speed [m/s]	13.4	17.9	19.7	14.7

3.3.1. *Theoretical design analysis*

Throughout the design iterations, the team relied on a combination of analyses, which will be discussed in this section, and the results of extensive system testing, which will be discussed in Sec. 3.3.4.

For each iteration, the system used for VTOL was designed first, and the aerodynamic platform was designed around it. The lift fans and EDFs were selected to provide enough cumulative thrust to counter 1.2 times the estimated gross weight of the vehicle for takeoff, landing, and hover. The vertical propulsion used two main fans near the nose of the vehicle to provide a majority of the required thrust and a third lifting fan downstream to control both pitch and yaw of the vehicle in hover. The wings were designed to place the center of aerodynamic lift behind the center of gravity of the hover configuration. The spanwise dimension between the main fans was constrained by the space needed for the avionics and payload equipment. For the Mark 1 vehicle, the main fans were embedded in the wing, and the rear fan was embedded in the horizontal stabilizer. Since the footprint of the EDF system in Mark 2 and subsequent iterations was smaller, all three EDFs were mounted in the center wing panel.

For the tailless vehicle design, the team relied heavily on Nickel and Wohlfahrt[7] to identify the most challenging aspects of the design and methods to approach these problems. The tailless vehicle design began with an airfoil selection. A reflexed airfoil, of positive camber near the leading edge and negative camber near the trailing edge, was chosen to provide a small positive pitching moment (nose up) to counter the negative pitching moment produced by the center of gravity being upstream of the aerodynamic neutral point of the vehicle. The center panel was designed using a thick custom airfoil in order to fully embed the EDFs and provide a large aerodynamic payload volume. The thin outer panels were swept backwards to produce a positive stability margin for forward flight. Additionally, twist was added to balance pitching moments.

To quickly iterate through the design space for each vehicle, Athena Vortex Lattice (AVL)[8] software was used to complete an aerodynamic analysis of the forward flight characteristics for each vehicle design. The method used in this code was based on a NASA program, detailed in Ref. 9. Designed for estimating the aerodynamics of complex geometries in subsonic flow, AVL provided predictions of the aerodynamic loads on the vehicle during forward flight. While the extended vortex lattice method assumes inviscid, incompressible, irrotational flow, these assumptions were valid for flight conditions in the design regime. This design tool enabled the team to determine the size and location of the two control surfaces based on their deflections during trimmed cruise and coordinated turns. Forces and moments about the aerodynamic center of the vehicle were calculated and used in the autopilot initialization of the fixed wing controls.

3.3.2. *Air vehicle development*

Upon completion of the initial analyses, the team began construction of the air vehicle. As manufacturability was a large portion of the UAVForge Competition, emphasis was placed on the team's ability to build the designed system based on available materials and tooling. Fabrication choices coupled with a stringent budget ultimately determined the materials and components used in the final system design. Weight budgets were documented for the vehicle throughout the process to ensure that the most updated gross vehicle weight was used at each iteration for platform design and the calculation of mission power requirements. A power budget was tracked to ensure that the designed vehicle would have enough battery capacity to complete the mission profile.

The first iteration of the vehicle, named "Mark 1", was sized based on the weight of components necessary to complete both VTOL and fixed-wing modes while carrying the necessary video and communications payloads. Batteries were sized to accommodate both the motor power required to conduct the mission and to provide the required power to transmit data up to a range of two miles during the three-hour "perch and stare" surveillance mission. Prototype vehicle construction consisted of custom-cut Dow blue 60 pounds per square inch (psi) foam for the wings, with balsa wood control surfaces, carbon fiber tail booms, and COTS carbon fiber landing gear. Conservative estimates of the total vehicle weight, coupled with iterative selection of forward and VTOL flight hardware, drove the sizing for the initial vehicle. As indicated in Table 1, the first iteration was the largest vehicle constructed during the competition.

For the second iteration, Mark 2, the vehicle underwent major configuration changes driven by the packing size requirement while maintaining the same hybrid vehicle concept. The reduced profile was enabled by the team's discovery of commercially- available EDFs, which allowed for smaller "lift fan" profiles embedded in the center wing panel. The aircraft's tail was eliminated because the EDFs were small enough to be packed into a flying wing configuration. The size difference between the Mark 1 and Mark 2 vehicles is easily seen in Fig. 4, where an outline of the Mark 1 vehicle is overlaid on the Mark 2 vehicle. While the main wing remained approximately the same size, eliminating the tail decreased the vehicle length by 64%. Moving from a traditional vehicle to a flying wing vehicle required additional analysis and hardware testing during the design and implementation process. As the team members had limited experience with this configuration, they had to quickly familiarize themselves on all aspects of flying wing design, with the added challenge of embedded EDFs. Additionally, during this iteration, the team tested a new material, building one of the prototypes out of an acrylic frame covered with MonoKote, a plastic film commonly used in hobby remote-controlled aircraft. While lightweight and easy to construct, these materials did not possess the required durability for flight testing and were eliminated from subsequent vehicles.

The third vehicle iteration, Mark 3, was driven by the desire for a more efficient vehicle and smaller packing footprint. By reducing the number of components and the size of the EDFs, gross weight was reduced by 44% as

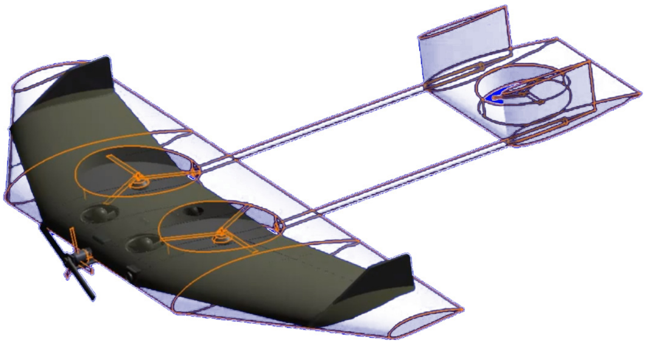

Fig. 4. Comparison of Mark 1 (outline) and Mark 2 vehicles.

compared to Mark 1 and Mark 2. Since the system design had matured and final components had been selected, the team decreased the built-in weight margins and redesigned the vehicle according to the new design specification. The weight decrease allowed further reductions in vehicle dimensions; the wingspan, characteristic of the vehicle size, decreased by 37%. In order to reduce the number of unique components in the system, the same EDFs were used in the fore and aft locations. Even though the thrust capabilities and weight distribution of the vehicle altered the dynamics for the VTOL and loiter flight modes, these changes also increased the vehicle's cruise speed and endurance during forward flight.

A final vehicle configuration, Mark 4, was the last redesign prior to the Fly-Off and was intended to address the problems encountered during system testing of Mark 3, as described in Sec. 3.3.4. Although the size and configuration was similar to Mark 3, the airframe was constructed from an EPP foam body over a carbon fiber skeleton. This change greatly increased the durability of the system to handling and impacts. The most significant change involved the shift to dual wing-mounted motors for forward flight. During hover to forward flight transition for the Mark 3 vehicle, the team found that the wake of the spinning forward propeller decreased the thrust of the EDFs, causing the vehicle to lose altitude. Therefore, the forward flight motors of Mark 4 were mounted on the wings to improve EDF performance during transition. Unfortunately, while implementing these changes, the team encountered additional complications that influenced the decision to decline the invitation to the Fly-Off Competition.

3.3.3. *Software and avionics configuration design*

In order to deal with both the manufacturing aspect of the challenge and the geographic diversity of the team, a key element of the team's strategy was the design of a modular system, both in the hardware design (e.g., easily swappable parts) and testing (e.g., testing forward flight and hover modes independently). The software and avionics had to be designed with modularity in mind in order to not impede the development process. First, the team decided that the avionics hardware would consist predominantly of self-contained, off the shelf components; no custom avionics hardware would be produced. This applied to the autopilot, radios, and sensors. Next, in accordance with the test plan, it was decided that the software developed needed to be modular so that, for example, the autopilot could be pulled from the forward flight test vehicle and immediately put in the hover test vehicle without software changes. Finally, due to the compressed timeline and collaborative nature of the competition, the team decided to base the software of an existing open source code base. This foundation would cut down on development time and, upon successful development, would allow for sharing the code with the larger do-it-yourself (DIY) community.

These requirements led to the selection of the ArduPilotMega autopilot hardware and ArduPlane/ArduCopter software systems from the DIYDrones community.[10] The ArduPilotMega, an Arduino-based platform, contains all the flight critical sensors, processing hardware, and interfacing hardware in one convenient, low weight package. During the competition, version 1.0 of the ArduPilotMega was used, since version 2 was released too close to the final Fly-Off to justify switching over. In addition to the autopilot and its built-in sensors, the avionics hardware also consisted of a magnetometer, a downward looking sonar sensor to aid in landing, a pitot tube and pressure sensor to measure airspeed during forward flight, and a charge coupled device (CCD) camera to collect and transmit video from the vehicle.

Most commonly, either the ArduPlane or ArduCopter codebases are used with the ArduPilotMega hardware. These two projects contain many identical features relevant to the final design, including: waypoint and flight corridor control, automated safety procedures for loss of communication events, and a fully integrated telemetry and command protocol (MAVLink). However, the ArduCopter and ArduPlane projects are separate builds, each providing functionality for a different class of aircraft (rotorcraft and fixed wing vehicles, respectively). Due to the unique aspects of the hardware platform, the team could not simply use either build of the autopilot software out of the box; instead, components from each build needed to be combined. The software team designed a custom build of the firmware that integrated the tricopter stabilization, auto landing, and auto launch code from the ArduCopter build along with the fixed wing stabilization and waypoint following code from the ArduPlane build. The most challenging and novel element of the custom firmware was the transition between the two modes. In the transition mode, stabilization was performed by running tricopter and fixed wing stabilization in parallel while mixing their control signals, weighted by airspeed. At lower airspeeds, the control signal from the tricopter stabilization would be weighted strongly, and the control scheme would smoothly switch over to fixed wing stabilization at higher airspeeds. During initial testing, the hover operating mode was developed and tuned using a kit-built tricopter test bed. The hover mode was then tuned for each vehicle iteration at the beginning of its test phase. A similar process was followed for the forward flight operating mode of the custom build. Each of the individual operating modes of the custom build was successfully demonstrated in at least one milestone video. However, due to the previously mentioned issues preventing participation in the Fly-Off and the tests described in Sec. 3.3.4, the transition code was not fully tested. The team decided not to publicly release the modified builds until the modifications could be fully tested.

Communication with the vehicle for telemetry and control occurred through a 100 mW, 900 MHz XBee-PRO XSC radio link. The antenna on the aircraft was a V-Dipole antenna, chosen for its light weight and low profile. A 900MHz, +10dBi Yagi antenna was used for the ground-based link. The video surveillance imagery was captured by an onboard CCD camera operating at a resolution of 494 × 768 pixels and an average frame rate of 30 frames per second. This analog video was transmitted to the ground station by a separate 1.5 Watt radio. Both 900 MHz and 1280 MHz transmitters were explored for this link, but the 1280 MHz link was chosen to minimize interference with the telemetry link. Several of the team members possess amateur radio licenses, allowing the video transmitter to be used at the frequencies and powers noted. Ground-based testing of the telemetry and video hardware demonstrated a range of approximately 1.25 miles in NLOS conditions, and development was still in progress at the time of the Fly-Off to reach the 2.0 mile requirement.

3.3.4. *Flight tests and results*

Conducting flight tests for each of the vehicle iterations was crucial to the design and validation process, but was also time consuming. At each design stage, the team identified incremental objectives that the system would achieve. For the first prototype in the Mark 1 configuration, the team tested for stability in the tricopter configuration fully integrated into the fixed-wing platform. This test demonstrated that the on-board power system was not able to supply the necessary current to all of the lift fans simultaneously. Also, the rear pivoting lift fan was undersized for yaw control and needed a structural redesign to function as expected. The first integrated flight test demonstrated feasibility of the tricopter configuration embedded in a traditional fixed wing system, but also highlighted several opportunities for design improvement. In addition, this test illuminated the team's need for independent component testing prior to integration into a final system.

After a significant redesign from the conventional configuration to a flying wing configuration, the Mark 2 tests were conducted using two similar vehicles; one vehicle was built to perform the forward flight task, simulating the vehicle's movement to and from the surveillance site, and the other vehicle was outfitted to perform the VTOL and hover tasks, simulating the takeoff and landing procedures at the beginning and end of the mission as well as arrival and departure from the surveillance site. At this point, the autopilot was integrated into the system in order to test the hover and forward flight modes independently. These

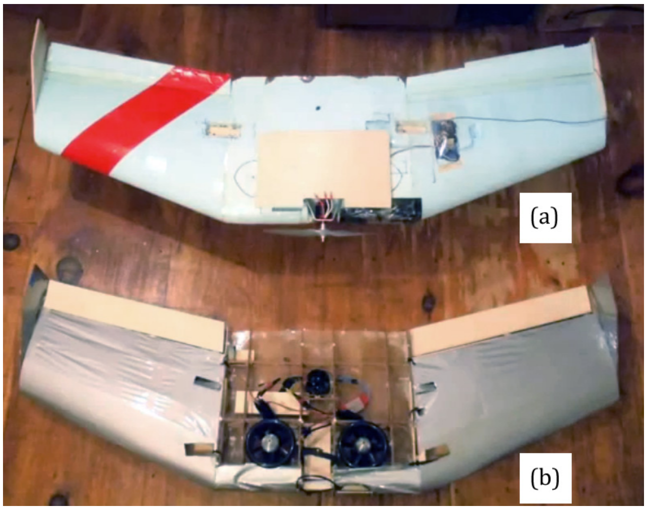

Fig. 5. Comparison of Mark 2 prototypes: (a) Forward flight prototype; (b) VTOL prototype.

prototypes can be seen in Fig. 5. Both vehicles were of identical size and of similar weight distributions.

As demonstrated in the team's Milestone 2 video,[11] this vehicle design was able to perform both VTOL and forward flight functions independently. The novel embedded EDF design was perhaps the most significant feature requiring evaluation in flight test. The protruding EDF bodies disrupted the airflow, creating additional drag and reducing the lifting surface area of the center wing. After ensuring the capability of EDF power to lift and control the vehicle, feasibility flight testing of the combined EDF and fixed wing system was conducted on the fixed-wing prototype. The EDFs were first simulated by mounting cylindrical tubes into the forward-flight wing to test the effects of a disrupted airfoil surface and the protrusions in the airstream. Cylinders of varying heights were installed on the forward flight test air vehicle, and the results of these flight tests were then used to adjust the aerodynamic models. This evaluation, first performed on Mark 2, was repeated for the later iterations as well. With this configuration, the forward flight prototype demonstrated its ability to complete a rolling takeoff and maneuver in flight.[11] During Mark 2 hover tests, it was determined that the rear EDF was too small to adequately control the vehicle's pitch and that more design work was needed to create a stable platform in the hover configuration. During testing of the Mark 2 design, both prototypes suffered structural damage, further motivating a redesign of both the vehicle structure and the manufacturing process.

The testing of the Mark 3 prototype was driven by the outcomes of the Mark 2 prototype tests. Fully integrating both VTOL and forward flight capabilities intoa single prototype, this was the first time the team flew a fully assembled vehicle. In this prototype, the rear EDF from Mark 2 had been replaced by the larger EDF used in the main wing to improve yaw and pitch control during VTOL and hover. In addition, these flights marked the first test of the autopilot mode for transition from hover to forward flight. The ground control station was integrated into the system and tested, allowing the operator to receive both telemetry data and live video from the onboard camera. In Milestone 3, the Mark 3 prototype performed well despite a major hardware malfunction in the minutes prior to the live video demonstration; the demonstration included vertical takeoff, hover and circle at a specified altitude, and concluded with a vertical landing.[12] As previously described, the successful completion of this milestone earned the team an invitation to the Fly-Off Competition. However, at this stage, attempts to perform transition from VTOL to forward flight showed that the use of the single propeller upstream of the EDFs greatly disrupted the flow to the EDFs, decreasing their thrust and ultimately losing significant altitude before forward flight could be achieved.

The inability to transition due to the positioning of the single propeller for forward flight led to the redesign for Mark 4. As mentioned in Sec. 3.3.2, the Mark 4 vehicle featured dual propellers on the outer wing panels, away from the center panel containing the EDFs. However, attempts at rolling takeoffs were unfruitful due to control complications with the dual propellers combined with manufacturing defects in the landing gear and forward motor mounts. Manual transition to forward flight from hover was also attempted, but the control complications persisted and successful transition was not achieved for the final vehicle design.

4. Discussion of Challenges

Despite the apparent simplicity of the mission profile, this competition sought to tackle an exceedingly difficult problem. The failures and challenges that arose highlight the need for specific technology improvements in the UAV domain, primarily in radio hardware and power systems.

4.1. *Technical challenges*

The team encountered the single largest technical challenge while designing the communications system. With the intent of supporting tactical operations, where the presence of external networks is uncertain, the team selected point-to-point radios for communication rather than cell network-based communications. However, for both the video and telemetry communication links, the small payload capacity of the vehicle and the required 2.0 miles NLOS range constrained the selection of commercially available transmitters. After field testing several transmitters that claimed to meet the required specifications, icarusLabs found that the transmitters that were small enough to meet size and duration requirements fell short of the required transmission range. Additionally, increasing transmitter power can be difficult due to restrictions imposed by the United States' Federal Communications Commission (FCC).[13] Further research is needed in the area of small, lightweight communication platforms in order to allow for reliable, long-range control for small aerial systems.

Because of repeated iterations in the airframe design, the avionics group did not have consistent access to a reliable system on which to prove out avionics hardware and mission profiles with enough time before the Fly-Off Competition. Late in the competition, a tricopter kit was acquired for baseline avionics testing. In hindsight, earlier investment in a development platform, such as a COTS tricopter or quadrotor, would have enabled the avionics team to diagnose and correct problems with the more generic UAV components earlier in the development cycle. As exemplified by large successful aerospace industry programs,[14] many projects to design a new airframe can benefit from developing and testing on a proven surrogate aircraft to solidify subsystem confidence.

Another major technical challenge involved the power requirements for the system. As with any aerial system, design of a UAV involves a constant trade-off between size, power, and weight requirements. Due to the range and duration requirements of the mission, the necessary batteries accounted for almost 40% of the vehicle weight in the final system configuration. Advances in battery technology to create smaller, lighter power cells will increase UAV flight duration, enhancing both range and persistent surveillance capabilities.

4.2. *Logistical challenges*

In addition to the technical challenges, icarusLabs also faced several logistical challenges, the greatest of which was the geographic distribution of the team. As mentioned in Sec. 3.1, the team used a combination of collaboration tools in order to stay organized and ensure that documentation could be maintained in a centralized location. Redmine served as the core of the team's data centralization strategy, featuring a wiki, which allowed the team to compile the most updated design information for the vehicle, and an issue tracker, through which the team could track progress on subtasks in order to meet deadlines. Additionally, linking Subversion to Redmine allowed for easy synchronization and sharing of materials and work products. Etherpad was another core tool, enabling the team to write documents collaboratively. Also, given the decentralized nature of the team, the video communication capabilities of Google Hangouts proved invaluable for real-time discussions. Overall, the icarusLabs team felt that its approach to the organizational aspects was very successful and that its solution highlights the wide range of freely available tools, which are a huge asset to geographically distributed teams.

The numerous flight tests demanded the most organization, requiring coordinated shipments and travel to transport hardware and test personnel to the testing locations. Recommendations for future teams would include building and developing at least two copies of the vehicle, one for each test location, in addition to a baseline avionics development vehicle discussed above. Because of limited available funds, this dual build was not feasible at the time. In addition to facilitating logistics, multiple airframes would benefit avionics and system testing. Because of the single and quickly varying airframe, the icarusLabs autopilot development lagged behind that of the flight vehicle. However, one testing strategy that did work well was recording videos of each and every flight test, which allowed team members not physically present to celebrate the team's successes as well as help diagnose problems.

An additional challenge was finding suitable available testing locations, as most team members lived in urban environments with limited space to fly small aircraft. Even in nonurban areas, flying fully autonomous systems is highly restricted in the United States. Additionally, during the majority of the months from September to May, the weather in the northeastern states is not conducive to flight testing. Despite having a solid strategy to combat these and other organizational challenges, hardware difficulties and last-minute system failures prevented participation in the final Fly-Off Competition.

5. Reflections on the Competition

5.1. *UAVForge's crowdsourcing model*

The DARPA implementation of the crowdsourcing model in the UAVForge Competition led to a unique experience that encouraged competing teams and registered users to provide feedback on competition entries. While the UAVForge Competition was based on the principle of crowdsourcing, the competitive nature of the challenge itself led to the breakdown of collaboration between competing teams. In crowdsourcing, ideas and experience are solicited from a broad pool of people and meritorious solutions are able to advance through feedback and collaborative development. Due to the competition aspect and lucrative reward, teams often presented limited information regarding their designs in order to protect proprietary information. Consequently, most of the constructive feedback sought concrete design details to properly assess the feasibility of presented solutions.

Despite the conflict between collaboration and competition, icarusLabs generally found the comments and feedback received from other teams to be helpful, and the comments improved both the design and conveyance of the team's ideas. In an effort to uphold the crowdsourcing model, the icarusLabs team maintained a website[2] where design specifications and features were described in detail. Much like the open-source communities the team relied on for troubleshooting hardware and software components, comments and votes from competing teams helped icarusLabs think critically about the details of the proposed design. The access to a larger pool of technical knowledge resulted in rapid internal design reviews, leading to system improvements.

5.2. *Infrastructure and organization*

DARPA managed the competition through the UAVForge website, which included forums, direct messaging, and milestone video posting with feedback capabilities. At the beginning of the competition, the original website was difficult to use and some competition goals were ambiguous. However, DARPA was very receptive to feedback from the competitors regarding the platform, the details of the requirements, the voting system, and the competition as a whole. For example, the initial voting scheme rated each team's designs using a "crowd score" based on raw numbers of positive and negative votes. The organizers quickly realized that this format favored larger teams and subsequently adjusted the rating system to account for factors beyond raw crowd votes in order to grant smaller teams similar visibility. Additionally, DARPA made significant improvements to the usability of the site as the competition progressed. DARPA's willingness to address the competitors' issues and its ability to rectify problems was one of the successes in the UAVForge Competition.

While UAVForge encouraged cooperation between geographically separated individuals, the competition provided few tools necessary for facilitating successful collaboration. A consequence of the lack of tools manifested itself in team composition; most teams consisted of already existing communities and groups with few individuals seeking to collaborate beyond the minimal contact required by the administrators. In future endeavors, icarusLabs hopes that competitions like UAVForge will further expand the infrastructure available to competitors, such as a workspace in which teams could collaborate both internally, through the private sharing of designs and software, and externally, through the ability to publicly post basic design details for feedback beyond the mandatory milestone videos.

The fast-paced milestones provided a particular challenge for the competition. The competition milestones and the live demonstration allowed each team to present its solution to the community using a two-minute video. However, the video submissions for completion of the milestones varied greatly in the information the teams presented. Subsequently, by the time of Phase II, the Fly-Off Competition, few teams had mature designs that would have been able to proceed to Phase III, the Operational Exercise. Additionally, from the results of the Fly-Off Competition posted on the UAVForge website, it appeared that none of the teams in attendance achieved the Baseline Objectives set forth during Phase I. To better evaluate the feasibility of the designs, video milestones should have included more stringent requirements regarding the technical content that must be included for successful completion. Given that the competition only spanned nine short months, greater definition of technical checkpoints along the way would have helped each team receive more constructive feedback at each stage, possibly leading to a more successful final product.

6. Conclusion

The DARPA UAVForge Competition embraced a crowdsourcing model for system development, asking engineering enthusiasts to help each other find solutions to a difficult problem. As most of the icarusLabs team members were recent college graduates, this competition provided an excellent forum for applying specialized skills and systems engineering knowledge to a real problem. Despite the limitations of the crowdsourcing model, the interactions allowed for helpful discussion among teams, which helped improve design quality and generated a wide range of solutions. By attracting participants from all around the world, this competition and similar efforts will hopefully enable further collaboration among members of the international unmanned systems community. Furthermore, the approach encouraged a variety of solutions, including a number of unique designs that might never have made it through a typical proposal process. This type of creative thinking and innovation will be crucial as this industry moves forward to design novel, mission-effective, and cost-efficient solutions. The authors on behalf of the icarusLabs team would like to thank DARPA for sponsoring the competition and will be eagerly awaiting the next challenge.

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