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Winning the DARPA UAVForge Challenge 2012 — Team HALO

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UAVForge was a Defense Advanced Research Projects Agency (DARPA) and Space and Naval Warfare Systems Center, Atlantic (SSC Atlantic) initiative to leverage the exchange of ideas among an international community united through common interests and inspired by creative thought. More than 140 teams and 3500 registered citizen scientists from 153 countries participated in this year long event. From several selection rounds, a core of nine teams competed in the fly-off event and in June 2012 Team HALO from the UK was declared the winner scoring 47.7 points out of a total of 60 points, with their co-axial tri-rotor, Y6 (VTOL) small Unmanned Aircraft System (sUAS).

Keywords: DARPA; SSC Atlantic; UAVForge; sUAS; multi-rotor; crowd sourcing; NLOS.

1. Introduction

The DARPA/SSC Atlantic UAVForge crowd sourcing challenge, announced in July 2011, was designed to bring together a diverse group of UAV enthusiasts to develop the next generation, low cost, small Unmanned Aircraft System (sUAS) for perch and stare operations in a military context. The challenge combined a web-based collaboration site with a live competitive fly-off event held at Fort Stewart, Georgia, USA in May 2012. The target unit cost per system, set by the organizers, was US$10 k. This is not the first time that DARPA has used a crowd sourcing approach to develop next generation technologies and military systems.[1]

The field of small UAS has grown rapidly during the last decade.[2] Many of the early systems were based on fixed-winged radio controlled devices taken from the hobby market and improved with added features such as GPS and video downlink capability.[3] More recently the move has been towards smaller, lighter, more autonomous systems which have the capability to hover and perch with Vertical Take-Off and Landing (VTOL) as an essential, rather than a desirable feature.[4–8]

Several companies and research organizations, such as Aeryon Labs Inc., Transition Robotics Inc., EMT-Penzberg, Microdrones, AirRobot, Draganfly, Ascending Technologies (AscTec) and the University of Southampton have been developing multirotor UAS (more than one rotor) and these are now starting to enter the military and civilian markets with great success.

1.1. *The UAVForge competition*

The UAVForge concept called for a man-portable, VTOL sUAS to have the capability to be carried into a forward operating base from where it would be launched by a single operator on a mission to reconnoiter a target 3.2 km away in a Non Line Of Sight (NLOS) location, which consisted of an urban terrain environment, namely the Colmar UTS at Fort Stewart, Georgia, USA.

The challenge began with Milestone 1, a 1 min 'Concept Video Submission' stage which had the effect of stimulating debate and encouraging team formation. Teams consisted of individuals, companies, universities, as well as groups of

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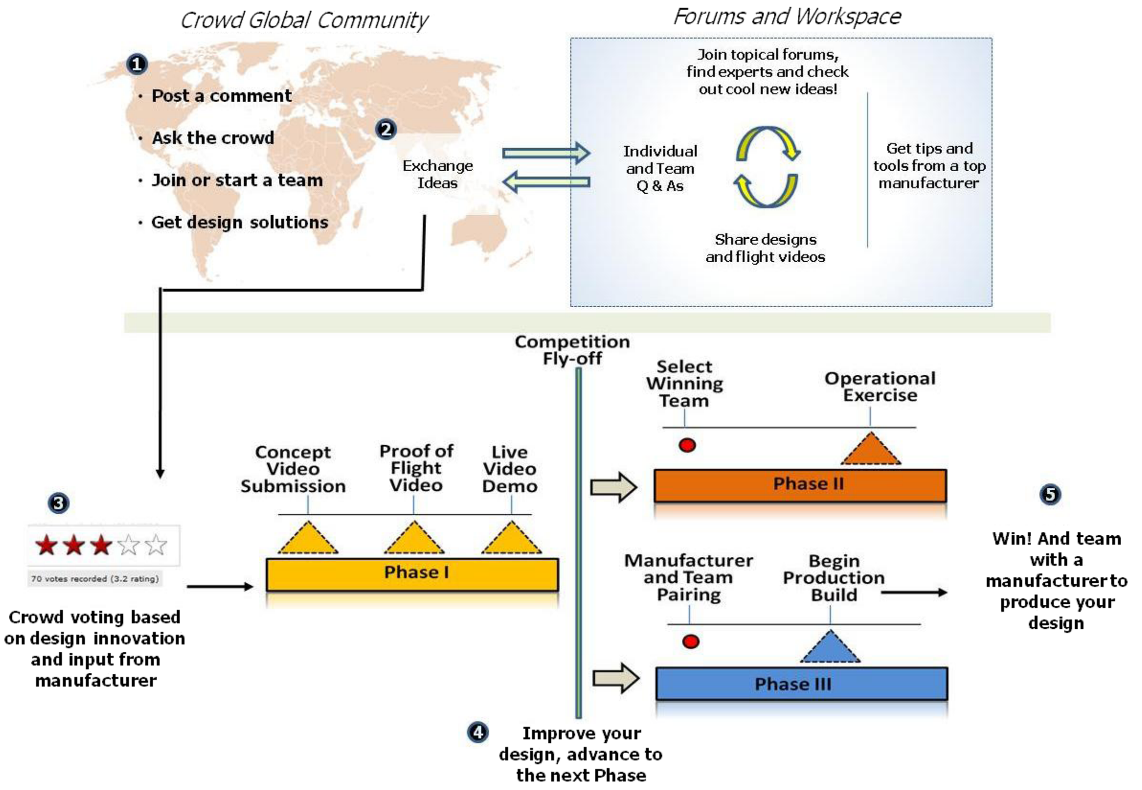

Fig. 1. DARPA's crowd sourcing model.[19]

enthusiasts brought together either by the challenge, or already working on Open Source UAV projects.[10]

As stated on the UAVForge website:

> "This challenge is guided by crowd sourcing. UAVForge provides you with the virtual environment and tools necessary to collaborate, independent of geographic location, education, profession, or experience. Individuals, *ad hoc* teams or any other formative organizations are encouraged to submit innovative ideas, designs, algorithms, materials, etc. where other members of the crowd can respond, vote, comment and contribute".[9]

Fig. 2. Team HALO's proof of flight prototype.

By the deadline of November 2011, 48 CAD/simulation video submissions had been received. These consisted of rotary-wing as well as fixed-wing hybrids, tail sitters, ducted-fans, etc. One team suggested attaching a camera to an eagle and training it to fly the mission. By far the most prevalent proposal was a conventional quadrotor design in an 'X' or '+' configuration. Registered users had the opportunity to post comments, ask questions and ultimately score each design out of five stars. The top scoring team (4.13) at this point was a bespoke quadrotor design from MAAV — A team from the University of Michigan with sponsorship from Northrop Grumman. The HALO team's submission showing a simulation of Y6 UAV entering an urban area to search for likely targets was ranked 24th with a mid-range score of 2.4.

The next phase (Milestone 2) was a 1 min 'Proof of Flight' YouTube video. By the submission date of January 2012, 22 teams had entered. The necessity to prove that something could be built and could actually fly whittled down the entries by over 50%. The favorite at this point was the GremLion team (3.15) from the National University of Singapore with their single co-axial rotorcraft, moving up from second place in the previous round. At this juncture, the HALO team was also on the move, ranked 8th with a score of 2.61 with our detachable arm Y6 design.

Table 1. Final fly-off selection.

Team name	Country	UAV type
AeroQuad	Intl.[a]	Y6
ATMOS	Netherlands	Tailsitter 4-Rotor
DHAKSHA	India	Co-axial Quadrotor
Extractor X	Singapore	Tailsitter 4-Rotor
GremLion	Singapore	Single Co-axial
HALO	UK	Y6
icarusLabs	USA	Hybrid Ducted-Fan
Navy EOD	USA	Quadrotor
Phase Analytic	USA	Quadrotor
SQ-4 Recon	UK	Quadrotor
SwiftSight	USA	Quadrotor with wheels
WIDrone	Italy	Quadrotor

[a]The AeroQuad team was based in the US, but had an international mixture of team members.

The final phase (Milestone 3) before the fly-off was a 'Live Fly Demo' whereby each team had to operate their UAVs to perform a series of set tasks whilst connected via Skype to the organisers in the USA. Twenty teams entered this phase by the March 2012 deadline and the leader at this point was the DHAKSHA team (4.49) from MIT India, with their range of quadrotors and hexrotors. Interestingly, after using a filtered crowd rating system, the icarusLabs team from MIT in the USA came out top with a score of 3.59. Team HALO was ranked in fifth place with a score of 3.02.

Analysis of these systems showed the design choices: 35% Quadrotor, 20% Hexrotor/Y6, 10% Single Rotor, 10% Tandem Rotor/Co-Axial, 10% Quadrotor (Tailsitter), 10% Hybrid Rotor/Fixed Wing, 5% Octorotor. After further deliberation by an independent governmental judging panel, the top 12 teams chosen for the fly-off were announced.

As can be seen in Table 1 above, Quadrotors still dominated the field in the final fly-off selection. The members of the HALO team also participated in the SQ-4 Recon team and were therefore the only representatives from the UK and the only team to have two systems in the final selection. However, before the fly-off took place, three teams pulled out, either citing commercial interests (WIDrone, SQ-4 Recon) or system failure (icarusLabs).

2. Milestone 4 — The Fly-Off Event

2.1. *Target location*

The venue chosen for the fly-off event was the Colmar Urban warfare Training Site (UTS) at Fort Stewart, Georgia, USA. This was an old US Army base constructed during WWII and home to the 3rd Infantry Division. The base covered an area of 1100 km^2 and contained the recently built Colmar (UTS). Colmar consisted of a number of buildings arranged in a typical town complex arrangement.

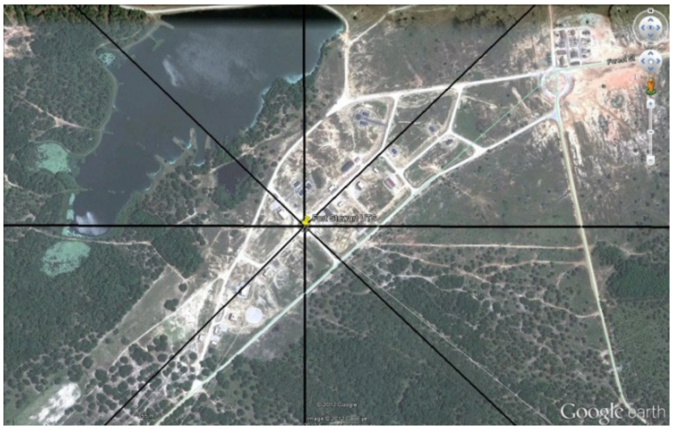

Fig. 3. Google Earth Map of the Colmar UTS.

2.2. *Mission scenario*

The mission scenario as set out by the competition organizers was stated as follows:

> "You are a member of a team and your mission is to outfit a fictional Task Force with an unmanned remotely operated micro air vehicle system. The entire air vehicle system must fit within a rucksack and a single person traveling by foot must be able to carry and operate the vehicle without assistance".[3]

> "The job of the Task Force is to conduct observations of suspicious activities occurring within the vicinity of two nondescript buildings in an urban area. Due to security in the region, all operations must be conducted beyond line of sight so as not to compromise your presence. If the UAV system is detected the mission will be jeopardized. The total observation time may require up to three hours of pictures and/or video to document the facts. Once key observations have been made, the team must quickly retreat to their designated rendezvous location. It is possible the vehicle will be handed off to another member of the Task Force to ensure mission success".[3]

Due to the nature of the task and the variety of the proposed solutions put forward, it was clear from the start that the perch and stare task could be achieved in a number of different ways. The UAVForge website stated that:

> "Once the vehicle has flown to the predefined search area, the vehicle needs to identify a vantage

point from which to conduct observations. This task can be accomplished by any means which includes landing, adhering, hanging, and/or hovering above or under a physical structure".[3]

Clearly there was a degree of ambiguity in the rules, which was designed to cater for an unknown type of UAV that could have been deployed, i.e. a blimp or a balloon. This would later be a source of debate as to when a system had actually met the requirements of the Baseline Objective.

2.3. *Technical performance requirements*

- The complete air vehicle system must fit in a rucksack, carried by a single person.
- The air vehicle must take off vertically from a starting location, fly out to an observation location, perform observations, return to an ending location that is different from the starting position, and land vertically.
- The air vehicle system must be able to fly and operate successfully in wind speeds of up to 6.7 m/s.
- At the target area, the air vehicle system must be able to identify persons or activities of interest up to 30 m away.
- The air vehicle system must send real-time video or pictures from its observation area back to the operator (a distance of up to 3.2 km).
- The vehicle design must consider noise reduction features to make it as quiet as possible.
- The air vehicle user interface and vehicle controls should be simple and intuitive.

2.4. *Scoring*

The scoring for the fly-off event was sub-divided into three elements (see Appendix A):

- Baseline Objectives (30 points)
- Advanced Behaviors (140 points)
- Manufacturability (30 points)

Therefore the maximum score was 200 points. Each of the Baseline Objectives was pass-fail, and all of the baseline objectives must have been completed in order to be eligible to earn points for advanced behaviors.

Teams were given the opportunity to conduct the Advanced Behaviors assessment before or after attempting the Baseline Objectives. The manufacturability assessment was conducted by Northwest UAV Propulsion Systems (experienced UAV manufacturers) contracted in by DARPA [11]. Each team had to submit a detailed Bill of Materials (BOM) which included pricing information, as well as upload CAD files for each manufactured component.

Fig. 4. HALO UAV having landed at the target location.

3. The HALO™ Small UAS

Team HALO's entry to the competition took the form of a Y6, co-axial tri-rotor design as previously illustrated. The concept for this was originally developed for the UK MoD Grand Challenge event held at the British Army's Copehill Down urban warfare training site on Salisbury Plain in August 2008.[12] The Y6 configuration has six rotors in total; two co-axial rotors, situated at three locations, as can be seen in Fig. 4.

3.1. *Co-axial propulsion theory*

Co-axial propulsion units have been deployed on both fixed wing and rotary wing aircraft with impressive results. The main benefit when used on rotorcraft is the inherent Yaw stability meaning that the tail rotor can be dispensed with thus saving up to 20% of the total engine power requirement.

The theoretical understanding of co-axial propulsion has been developed over a number of years by several researchers.[13–20] Figure 5 shows the interaction effects of the upper rotor on the lower rotor.

When analyzed using the simple momentum theory, this gives a 41% increase in induced power, relative to the power required to operate the two rotors individually. Although theoretically correct, this has been found to be overly pessimistic in practice, with the true value being closer to 15% when measured experimentally.[21]

A co-axial rotor unit can never be as efficient as two separate rotors. However, it has the advantage of being more compact when compared with an equivalent arrangement of the same size and number of single rotors.

In terms of a single soldier system, which was required to be carried into the field and operated with a low logistics

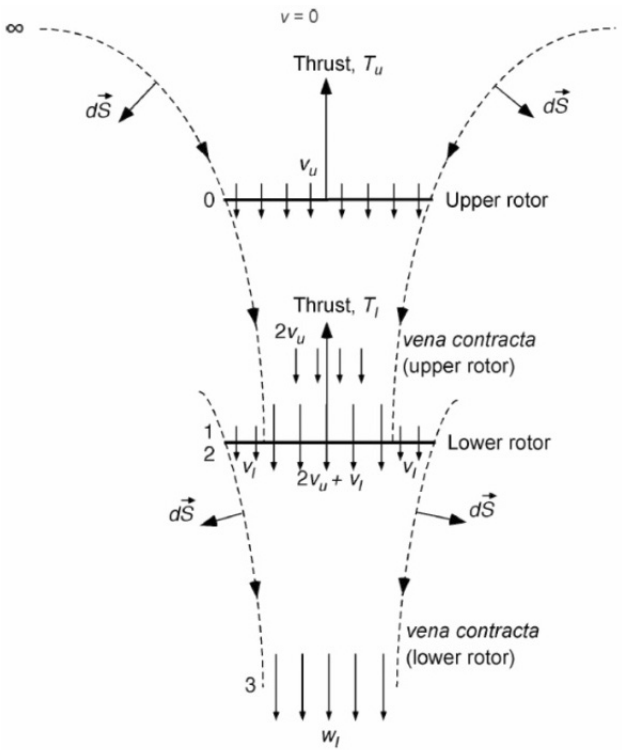

Fig. 5. Flow model of a co-axial rotor system.[19]

footprint, the co-axial arrangement was considered the optimum design choice for this particular application.

The three-arm arrangement lends itself to a balanced approach, provides stability and a degree of redundancy not found in the quadrotor configuration.[22] This means that the Y6 arrangement can still fly with up to two failed rotors, provided that these are not on the same arm.

Since seven out of the 12 finalists (see Table 1) were quadrotor designs, this became a significant differentiator between the teams. It is also of interest to note that three other teams used the co-axial principle in their designs. These consisted of AeroQuad (Y6), DHAKSHA (co-axial quadrotor), and GremLion (single co-axial).

3.2. *Design philosophy and constraints*

Throughout this year-long project, the design philosophy was to 'keep it simple'; in doing so the authors believe that they reduced the risk of failure, common on more complicated machinery and systems. The overriding design constraint was low mass, since every gram of mass would decrease the aircraft's endurance capability. Every component on HALO was therefore selected for functionality with minimal mass. Where two elements provided the same functionality, the lighter one was chosen.

3.3. *Design elements*

Having chosen the basic configuration of Y6 geometry, the team focused on the other components of the system. It should be stated at this point, that due to the need for stealth, ease of use and simplicity, an all-electric design was chosen over a heavier, noisier and more complicated fuel engine design. The other elements of the design consisted of:

Air Platform

- Fuselage housing the electronics,
- Power Supply — Lithium Polymer Battery,
- Speed Controllers,
- BLDC Motors,
- Rotors (Propellers),
- Camera and Video TX,
- Flight Controller,
- Landing gear.

Ground Control Station (GCS)

- Hard case to carry the air vehicle and GCS,
- Tablet computer housing the control software,
- Spare batteries and charger,
- Cables and Coax leads,
- Tripod and Antennae,
- Video RX,
- 7" Preview Screen,
- Digital Video Recorder (DVR),
- First Person View Goggles,
- Operator's Seat.

Having already decided to go for an all-electric version, the search began for a battery with an extremely high specific energy density (Wh/kg). The state-of-the-art, in terms of a low voltage dc rechargeable power source, which can provide continuous high current (20–40 A), is Lithium Polymer (Li-Po) chemistry used mainly in the hobby RC market. After an extensive search, a single MaxAmps (4 S) 11 Ah LiPo battery was selected. At over 800 g, this was the heaviest component of the air platform (33% of the total mass); however, it provided 162.8 Wh and had a specific energy of 203.5 Wh/kg. At a cost of US$300 each, these are fairly expensive; however, they provided a 40 C rating and are completely waterproof.

Having selected the power source, the search continued for an ultra-efficient BLDC motor and rotor combination. After conducting an extensive trial of several likely candidates, a 360 kV 5010-360 motor and 16 $\times$ 6.5 inch Carbon Fiber rotor combination from RC Timer based in Southern China was selected. These have the highest propulsion efficiency of any of the motor-rotor combinations tested to date (see Fig. 6).

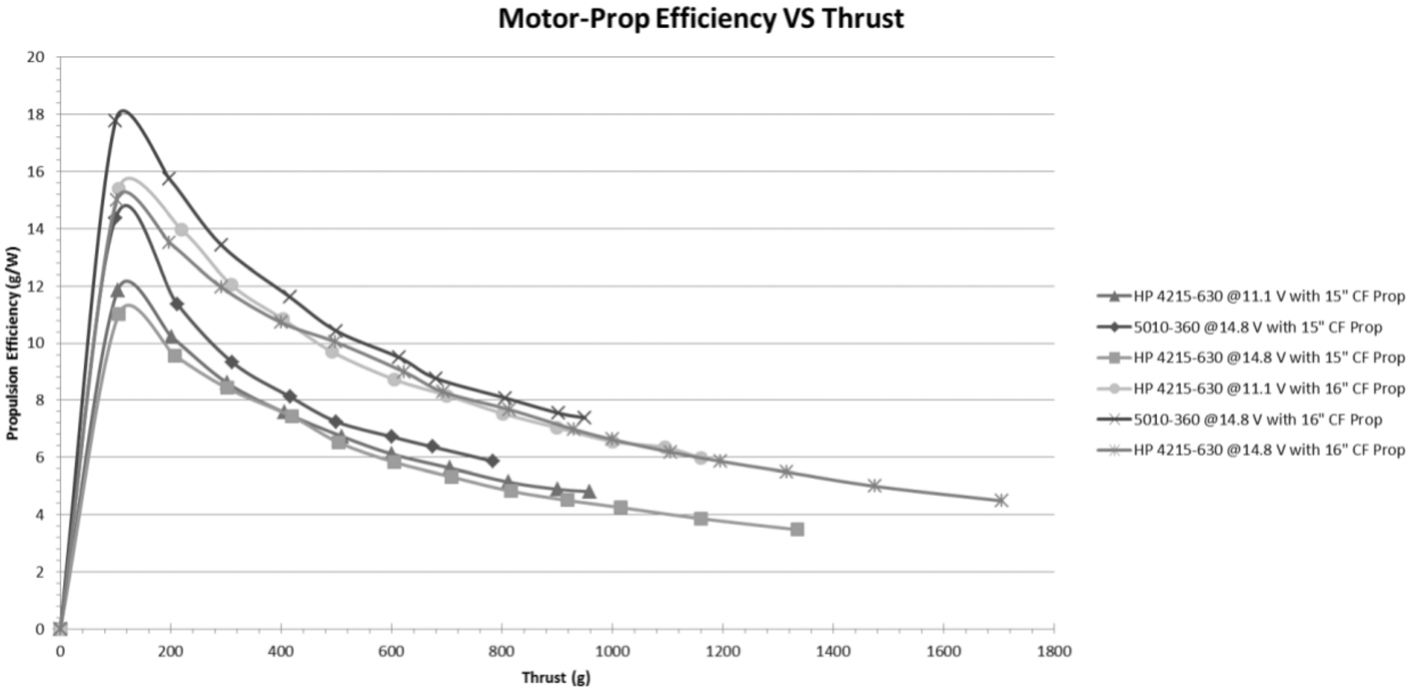

Fig. 6. Motor-rotor static thrust tests.

Due to the low current draw at hover (3 A/motor), it was possible to select very lightweight speed controllers and low amperage wiring.

One essential feature of our design was the detachable arms and legs which enabled the whole UAV to be broken down in seconds into a very small package size. This not only provided portability, but also meant that any damage resulting from a crash could be replaced easily.

The choice of the flight controller was determined by the need to have autonomous waypoint operation over a range of up to 3.2 km, whilst having a simple interface and also not too much cost. The DJI Wookong-M flight controller is a well-respected high-end RC system which costs approx. £1k, but had all the features that we required. A major drawback was that it was not open source and thus we could not custom program the system or incorporate 3rd party devices such as ultrasonic sensors for landing, etc.

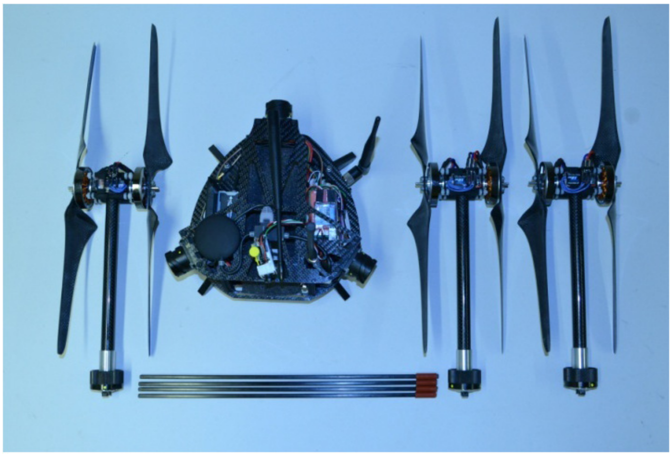

Fig. 7. HALO UAV showing detachable elements.

3.4. *HALO UAS specification*

- Air Vehicle Mass: 2.5 kg
- Endurance: 30 min+ (hover); Range: 6 km (max)
- Props: 16 inch Carbon Fiber
- 50 GPS Waypoint Control via Tablet Computer
- Automatic Take-off and Landing
- Flight Controller : DJI WK-M (900 MHz or 2.4 GHz)
- GPS, Altitude and POI Hold and Return to Home
- Failsafes – Low Battery, Loss of Comms, etc.
- 11 Ah Li-Po (4 S) Battery
- 1280 MHz, 2.5 W Video TX
- Detachable Arms and Legs (Quick release)
- Two Switchable 1 g Micro Cameras (one gimbaled)
- Ability to Land on Flat Ground or on a Roof Apex

The complete HALO UAS was self-contained within a single back packable flight case which contained the UAV, two Li-Po batteries, tablet computer, tripod, aerials, video RX, 7 inch preview screen, FPV goggles and operators seat. The total system mass was approximately 10 kg. The system set-up takes less than five minutes and with an optimum flight velocity of 10 m/s, the UAV has an operational range

Fig. 8. The HALO UAS set-up at the Colmar UTS (image shows the church in the background).

of approximately 6 km (max), the limiting factor being the capacity of the current generation of Li-Po batteries.

HALO was designed to have two 1 g micro cameras, one forward facing on a gimbal and one fixed at the center pointing directly downwards. The operator can switch between the two views at any time during the mission. The downwards facing camera is particularly useful for landing.

For the UAVForge mission scenario, the concept was to attempt a perch landing on the apex of the church which would provide an excellent viewpoint over the target area.

4. Problem Areas

All of the teams that attempted the Baseline Objective over the 10 day fly-off period at Fort Stewart encountered problems with data communications. The NLOS environment was not conducive to good RF communications. Even though this was anticipated, it still represented a considerable problem. When combined with possible interference (whether intentional or unintentional from other military operators on the site) this made the challenge much more difficult.

Analysis of the terrain elevation profile using Google Earth (see Fig. 9) provides some answers as to why this was

Fig. 9. Google Earth elevation profile at the Colmar UTS.

Fig. 10. Viewpoint at the launch site from about 25 m AGL, showing the range of high trees surrounding the area.

such a difficult task (the launch site is on the LHS and the target, at the center of the Colmar UTS, is on the RHS at a distance of 3.2 km). The target was situated over the hill.

When combined with the dense, 30 m high woodland which surrounded the Colmar UTS and the launch site, it was incredibly difficult to approach any landing location with good communications (data and/or video).

Each team tried to overcome this situation in different ways, some increased their RF output power (up to 7 W) without much luck and some teams decided to increase the height of their antennae using large tripods or a helium balloon, sometimes combined with high gain, directional Yagi antennae.

The HALO team, like all the others, experienced this issue during its first two flights. Whereas we could reach the target using GPS waypoints, every time that we reduced

Fig. 11. Elevated Yagi antennae being deployed by one team.

Fig. 12. Emplacing a high gain 13 dBi Yagi 1.3 GHz antenna in a tree at 25 m AGL using the bucket loader.

the altitude we lost video comms. This would occur at around 50 m AGL.

Our initial response to this was to increase the height of our Yagi antenna (13 dBi) by emplacing it together with the receiver in a tree about 25 m AGL which improved the range. However, comms over the target were still not reliable enough to attempt a landing. On the last but one day, a test was conducted with a higher power 1280 MHz video transmitter moving from 1.5 to 2.5 W. This setup provided good video comms all the way down to roof top height during a range test with HALO flying over Colmar under manual control and the GCS situated at the launch site.

Table 2. Final ranking and score.

Rank	Team	Final Score
1	HALO	47.7
2	AeroQuad	39.1
3	ATMOS	37.3
4	SwiftSight	37.3
5	Navy EOD	36.5
6	Extractor-X	32.0
7	DHAKSHA	31.5
8	Phase Analytic	30.5
9	GremLion	19.2

On the final day, during an attempt to land on the apex of the church roof, the GPS signal was lost whilst on route to the target. This caused the air vehicle to have an uncontrollable landing in trees which caused major damage and was not repairable in the field.

Subsequent analysis (see Fig. 13) showed that at the exact time of the accident (08:20–08:30) there was a very weak GPS signal (only three satellites) caused by a constellation dropout. In hindsight, the predictor software tool should have been used as a matter of operational process.

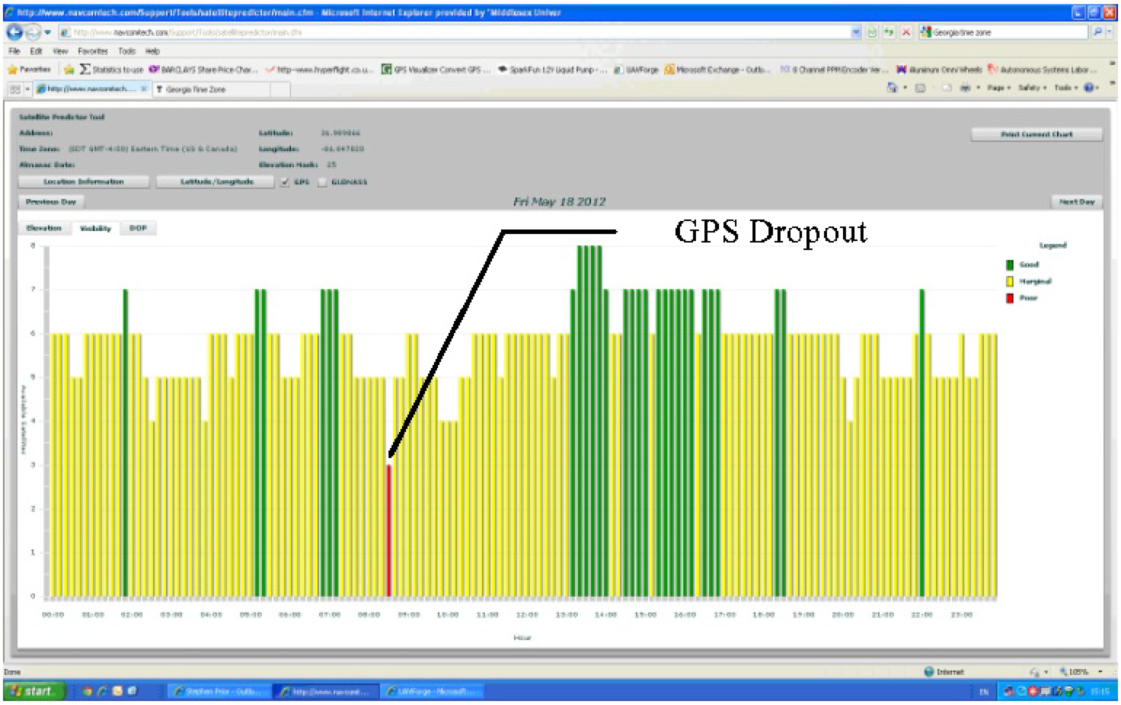

Fig. 13. Satellite predictor tool showing GPS dropout.[23]

5. Results

Several teams attempted the Baseline Objective on multiple occasions with partial success. However, the HALO team was the only team to score some points under every scoring category. The final scoring of the challenge was announced on the UAVForge website in late June 2012.

DARPA stated that as none of the teams had successfully completed the Baseline Objective, there would be no award of the US$100k prize and no follow on operational exercise or production of up to 15 units for trials with military units. This was a very disappointing result!

It is important to note that the above score is out of 60 points and relates only to the first and third scoring elements (see Appendix A). If we were to include the Advanced Behaviors scoring elements then our score would be an estimated 150 points out of a total of 200 points. The only element of the Advanced Behaviors that was not attempted by the HALO team was the obstacle avoidance task. This was due to the fact that the flight controller was not open source and therefore could not be modified in terms of 3rd party interfaces.

6. Conclusion

When the UAVForge event was first publicly announced, wired magazine called this challenge "Beyond the Beyond",[24] which is an apt descriptor for this difficult endeavor.

Some commentators have labeled this challenge a failure, since none of the teams successfully passed the Baseline Objective and the prize was not awarded. However, it should be remembered that all of the entries were experimental aircraft, built by enthusiasts in their own time and largely out of their own funds. Some people have criticized the inability of any of the systems to perch and stare at the target location, which was 3.2 km NLOS from the launch site. However, all of the fly-off systems cost less than US $10k, many costing less than $5k.

It is rumored that the AeroVironment Shrike quadrotor (estimated cost US$150k each) was tested over the same course prior to the fly-off event and that it too had problems with data communications and could not perch and stare for the required time. The Shrike was developed over four years, funded by DARPA to the tune of US$4.6 m[25]; if this system struggled with the course, it was perhaps no surprise that less resourced systems, costing a fraction of this, also struggled. If success is measured by how many DIY UAV enthusiasts are out there, and how far such systems have come over the last decade, then UAVForge was a resounding success.[26]

Two elements of the challenge stand out as warranting further attention: NLOS communications and the inability to land tactically and observe for up to 3 h. The first will require careful design of small, lightweight and directional antennae. The second will require an intelligent landing system which can cope with uncertainty.

The Y6 co-axial configuration (ranked 1st and 2nd) has proved itself an ideal platform for such surveillance tasks. Further development of HALO will include reducing the MTOM to below 2 kg, which should increase the endurance to approximately 45 min at hover. We are also looking at active directional antennae, digital video links and improved battery technologies, such as Lithium–Sulfur (Li–S) which could increase the specific energy to 600 Wh/kg by 2016.[27]

7. Acknowledgment

The authors would like to thank DARPA and SSC Atlantic for hosting the challenge, which spurred on innovations in this exciting area of unmanned aircraft systems research.

Appendix A. DARPA/SSC Scoring Schedule

	Points
Baseline objectives	
1. Conduct operations, preflight, and safety checks.	5
2. Perform vertical take-off and flight within specified altitude.	5
3. Orient heading and fly to observation area.	5
4. Transition from flight mode to surveillance mode and conduct observations for the time specified.	5
5. Complete observations and transition from surveillance mode to flight mode while maneuvering around obstacles.	5
6. Exit observation area, transition to specified altitude and land back at home base at the Flight Preparations area.	5
Sub total	**30**
Advanced behaviors	
1. Demonstrate safety in flight during a "communications out" condition.	5
2. Demonstrate an autonomous transition from flight mode to observation mode for surveillance and then transition back from observation mode to forward flight.	25
3. Demonstrate a simple user interface and vehicle controls which exhibits ease of vehicle operations with minimal pilot workload.	25
4. Mitigate the vehicle's acoustics signature level in flight and transition to observation mode.	25
5. Demonstrate an integrated obstacle avoidance capability.	15
6. Successfully execute the "Follow Me" task, which requires the vehicle to autonomously follow the ground operator from the Starting Point back to the Flight Preparation Area.	15
7. A complete parts list, including all (COTS) parts, to support the manufacture and innovation of the vehicle system.	30
Sub total	**140**
Manufacturability	
1. Assessment of the Producibility/Manufacturability of the UAS, based on the design information and BOM.	30
Sub total	**30**
Total	**200**

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