Development of a Co-Axial Tri-Rotor UAV

Dr Stephen D. Prior, Dr Mehmet Karamanoglu, Siddharth Odedra,
Mehmet Ali Erbil and Tom Foran

Middlesex University
School of Engineering and Information Sciences
Department of Product Design and Engineering
Trent Park Campus
Bramley Road
London N14 4YZ

s.prior@mdx.ac.uk

ABSTRACT

This paper discusses the initial design requirements and development of a Small Unmanned Aerial Vehicle (SUAV), sometimes referred to as a Miniature Aerial Vehicle (MAV) or Micro Unmanned Aerial Vehicle (µUAV) as the backdrop to an entry for the MoD Grand Challenge Event 2008 (MoD GC 2008).

A review of 61 SUAVs has been undertaken together with the development of a methodology for evaluation, review and rating against specific design criteria. This analysis concludes with a list of the top ten systems currently available which have been found to be best suited to the particular requirements of operating in the cluttered urban environment. Finally, we present a novel design of Co-Axial Tri-Rotor UAV (named HALO™) which has been developed by the i-Spy team at Middlesex University as our entry to the MoD GC 2008.

Keywords: Small Unmanned Aerial Vehicle, VTOL, Co-Axial, Tri-Rotor, MoD Grand Challenge 2008.

BIOGRAPHIES

Dr Stephen D. Prior gained a BEng Mechanical Engineering degree in 1987 and PhD in Rehabilitation Robotics from Middlesex University, London in 1993. He is a Chartered Mechanical Engineer, Corporate Member of the IMechE and Fellow of the Higher Education Academy. His research interests are in the areas of Mechatronics, Autonomous Unmanned Systems, Robotics and Design Education. He was project leader for the MoD Grand Challenge i-Spy team.

Dr Mehmet Karamanoglu heads the Product Design Research Centre at Middlesex University, London. He has a Bachelor of Engineering degree in Mechanical Engineering and a PhD in Numerical Methods. His current research includes developing design strategies for implementing mass customisation using post-industrial design processes and unmanned air and ground vehicles.

Sid Odedra gained a BA Product Design degree in 2004 and an MSc in Design Engineering in 2005. Sid is now a PhD student and tutor at Middlesex University. His PhD focuses on improving the terrain capability of UGVs for autonomous applications. His research interests reside in military robotics and autonomy.

Mehmet Ali Erbil is a 4th year student, currently studying for a BSc degree in Engineering Product Design. For the past year he has dedicated his time to the MoD Grand Challenge. He also competes in international competitions such as Eurobot and World Skills. His interests are Robotics, Mechatronics and Automotive Technologies.

Tom Foran is a 4th year student, currently studying for a BSc degree in Engineering Product Design at Middlesex University. His interests involve Mechatronic Applications, including programming and previous triumphs include Autonomous Dancing Robots, Robotic Pole Climber, Eurobot and World Skills.

Introduction

It has been reported that within the next decade 75% of the world's population will be living in urban areas [1, 2]. It can be extrapolated that future combat missions will involve operating more within the urban context with all its associated problems of identifying the threats posed by enemy fighters. This has to some extent already been borne out by the dual conflicts in Iraq and Afghanistan, where the US and British military have paid a high price for restoring freedom and have sometimes caused civilian deaths in the pursuit of this goal (see Table 1).

Table 1 – US, British and Civilian Casualties in Iraq and Afghanistan [3] [4]

Medical intervention in the combat zone during the so-called 'golden hour' has improved over time such that 9 out of 10 soldiers wounded now survive injuries that would have previously killed them, this is in comparison to the Vietnam war where the survival rate was approximately 75% [5]. Any loss of life is regrettable and the more that technology can do to remove personnel from the battlefield the better.

Conducting Military Operations in Urban Terrain (MOUT) is clearly more dangerous than operating in open terrain, and therefore requires greater situational awareness if casualties are to be reduced. The enemy's strength lies in their urban concealment and timing of an attack, whereas a regular army's strength lies in its superior firepower and technological innovations. One of the goals of the MoD GC 2008 is to tap into a pool of inventors and scientists who have previously not been involved in defence research.

The MoD Grand Challenge 2008

The MoD GC 2008 was loosely based on the highly successful DARPA Grand Challenges of 2004, 2005 and 2007 [6] whereby teams from across North America could enter autonomous UGVs consisting of adapted vehicles (trucks, cars and motorbikes) fitted with real-time sensors and software capable of navigating an unknown course in a limited timeframe. Winning teams were given cash prizes of up to US$2m.

The MoD GC 2008 was to create a system with a high degree of autonomy that can detect, identify, monitor and report a range of military threats in an urban environment.

The challenge offered a unique opportunity to develop low-cost, novel systems which could then be speedily deployed to operational theatres to combat the four main threats of IED's, Snipers, Technicals (4x4 armed vehicles) and Armed Combatants [7].

The MoD Grand Challenge team deliberately kept the brief as open as possible, stating that:

"The Grand Challenge will culminate in a competitive physical demonstration of an autonomous or semi-autonomous system in a representative urban environment at Copehill Down Village, on Salisbury Plain. It is envisaged that the system should be small and inexpensive whilst having utility in a wide range of circumstances. However, to simplify the nature of the physical demonstration it will be based on a relatively short-range reconnaissance of a village, prior to the entry of a foot patrol. Several potential threats will be positioned around the village, including in buildings. Systems will be required to detect these threats and provide sufficient information for the representative tactical commander to assess the threat and determine its position." (Excerpt from the Grand Challenge Website, 2008)

Teams were therefore given the opportunity to set their own design criteria based on this understanding of what the MoD wanted in terms of a demonstrable system.

The World of Unmanned Systems

Unmanned Systems now come in all shapes and sizes, and can be categorized in relation to the vertical plane:

- Space (Unmanned Space Vehicles, USVs)
- Aerial (Unmanned Aerial Vehicles, UAVs)
- Ground (Unmanned Ground Vehicles, UGVs)
- Surface (Unmanned Surface Vehicles, USVs) (Generally small boats)
- Sub-surface (Unmanned Undersea Vehicles, UUVs)

This paper will focus mainly on the design and selection of SUAVs due to their inherent suitability for MOUT in terms of speed, portability and stealth.

The 104% growth in the number of UAVs being developed over the last ten years has been impressive, driven in large part by the conflicts in Iraq and Afghanistan. According to estimates by Frost and Sullivan, the aggregate military UAV expenditure (2003-2012) for the US and Europe is expected to be £20bn [8], with the US DoD alone forecasting a FY09 UAS procurement spend of US$2bn [9].

The most up-to-date source of information relating to international UAV developments originates from the Unmanned Vehicle Systems Website and Yearbook which lists UAV activity across the international spectrum [10].

The latest data for 2008-09 lists 974 Unmanned Aircraft Systems (UAS) being developed in 49 countries throughout the world. Of these 974 systems, 578 (60%) are classed as military, 115 (12%) are civil/commercial and 242 (25%) are dual purpose. Other smaller categories are Developmental and Research.

In terms of the 49 UAS producing countries, the US leads with 341 (35%) systems, followed by Israel 72 (7%), France 65 (7%), Russian Federation 53 (5%), UK 51 (5%) and Germany 36 (4%).

The most common type of UAS remains the Fixed Wing system (71%), followed by Rotary Wing (18%), Shrouded Rotary Wing (Ducted Fan) (3%), Lighter-than-Air (3%), and then a series of other systems which include motorized parafoils, tilt rotors, flapping wings, etc.

Unmanned Aircraft Systems can be categorized according to their class; the UAS Yearbook lists these in three sections as Tactical, Strategic and Special Purpose (see Table 2).

Table 2 – UAS Categorization (Source: UAS Yearbook 2008-09)

Each of the services in the US have their own categorization of UAS, most use a Tier system where Tier I (Class I) is equivalent to Mini in Table 2. A good overview of this is given in [9].

In terms of MOUT, we are particularly interested in SUAV systems which fall into the categories of Nano, Micro and Mini, i.e. a Maximum Take-Off Weight (MTOW) less than 30 kg; this is mainly to aid portability by the dismounted soldier.

SUAV systems operating at very low Reynolds Numbers (≈ 20,000) suffer from unstable vortex shedding and laminar separation making them more prone to instability leading to control issues and inefficient flight. Current research into the use of very small UAVs is ongoing at a number of specialist labs in the US, Switzerland and France [11].

Figure 1 – Examples of Nano [12], Micro [13] and Mini [14] UAVs.

UK military UAV Capability

The British Armed forces first used the ill-fated catapult launched Phoenix UAV system during the Kosovo war in 1999 and 2000 where 13 were lost during operations [15]. The total cost of the programme was £227 million and each Phoenix aircraft is believed to have cost approximately £300,000. The overall initial purchase was for 198 units, it is not known how many were actually deployed.

In July 2005 a £700 million contract was awarded to Thales to provide the Royal Artillery with 54 unmanned air vehicles (UAV) named Watchkeeper designed for all weather, Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) use. Watchkeeper (WK450) will probably enter service in 2010. It has a payload capacity of 150 kg, an endurance of around 17 hours and an all up weight of 450 kg [16]. Watchkeeper is based on the Elbit Hermes 450 UAV design and ten units of this have been operating in Iraq with the British Army since June 2007.

As of 31 March 2008 the Phoenix system was removed from service and is being replaced in the short term by 3 MQ-9 Reaper UAVs which entered service in Afghanistan in October 2007 via a MOD urgent operational requirement [16]. Orders for ten more have been reported in the press.

In terms of SUAVs, the British have used the Buster UAV and more recently the Desert Hawk III UAV which reportedly costs about £50,000 each. In February 2008 the MoD reported that during operations in Afghanistan 27 units had been lost in the previous 12 months alone, this is out of a total compliment of about 184 units [15].

Future UCAV systems involve the development of the Taranis UAV, which is under development by a consortium led by BAE Systems. This will be one of the largest UAVs ever built with dimensions of 11 m long, 4 m high and with a wingspan of 10 m.

Autonomy

The key to a successful UAV is the level of autonomy embedded in the command and control structure of the unmanned system. A good overview of autonomy has recently been published by Frampton [17]. It is generally accepted that autonomy can be broken down into six levels ranging from Full Autonomy (Level 6) down to Full Human Control (Level 1). In terms of useful SUAV systems it is the author's belief that successful systems must at least be capable of operating at Level 4, which is defined as Human Supervised.

The Middlesex University Entry to the MoD Grand Challenge

A small group of staff and students based within the Department of Product Design and Engineering at Middlesex University, North London formed the I-Spy team to develop a system to enter the MoD GC 2008.

Our starting point in March 2007 was a position paper based on the MoD's outline rules [18] for the competition and our understanding of the possibilities of robotic systems in general. For the team this was the first project involving autonomous systems and thus was a steep learning curve.

Any solution to the MoD GC problem had to be Innovative, be of high Technical Quality, be Novel and have the potential for Exploitation.

Our initial brainstorming activity ruled out the use of UGVs due to the 90,000 m^2 surveillance area and the 1 hr operational window dictated by the MoD GC Rules. This led us to the following overview of viable options:

Table 3 - Overview of Viable UAV Options

From this initial assessment of the problem it became clear that all the options had something to offer in terms of a solution, however, the Rotary Wing (Helicopter) concept had the greatest potential.

From this table and in the light of a greater understanding of the problems associated with the dismounted soldier, such as the mass of any system, its endurance and performance we constructed a Preliminary Design Specification (PDS), the key points of which are given below:

Design requirements (in no particular order):

- MTOW of 5kg or less
- The system shall be capable of being backpackable (0.35 x 0.45 x 0.3 m = 47 lt)
- Linear Speed (0-3 m/s)
- Ability to hover and perch
- Endurance of 30-60 minutes
- Rate of climb in hover of 3.5 m/s
- Manoeuvrable in at least 4 DOF (X, Y , Z, and RZ)
- Ability to carry a payload of up to 2 kg (to include fuel/power source)
- Less than £5,000 (excluding sensor payload)
- Quiet in operation (< 60 dB(A) @ 3m)
- GPS waypoint autonomous control
- Autonomous vertical take-off and landing (VTOL)
- Set-up in less than 5 minutes
- Turnaround in less than 10 minutes
- Safe operation at all times
- Ability to detect, identify, locate and report the four main target types: IED's, Snipers, Technicals (4x4 armed vehicles) and Armed Combatants

The PDS was arrived at through debate within the team, with reference to the MoD GC rules and an understanding of the dismounted soldier through presentations from serving soldiers via MoD sponsored conferences and exhibitions. Based on this research a complete benchmark of all commercially available SUAVs around the world that met our design specification was undertaken.

With the help of many reference works, websites and online databases [19-28] we collected data on 61 UAVs (which represented almost the entire inventory of worldwide SUAVs) in the categories of Fixed Wing (17), Helicopter (12), Delta Wing (8), Ducted Fan (8), Multiple Rotary Wing (7), Hybrid (4), Lighter-than-Air (2), Para Glider (2) and Tilt Rotor (1).

Note that the requirement to hover/loiter can be associated (to some extent) with fixed wing and delta wing UAVs via their ability to circle overhead. Also it is important to point out that delta wing UAVs are a variant of fixed wing UAVs and are more prevalent in SUAVs.

The data collected consisted of System Name, Country of Origin, Website, Cost, Weight, Payload, Wingspan/Size, Endurance, Ceiling, Speed and Range. The next step was to decide on a range of criteria upon which we could rate each UAV system. After much deliberation we decided on the following ten criteria and associated weightings:

Table 4 – Selection Criteria & Associated Weightings

Each system was then graded out of 10, according to how well it matched the criteria, with a grade 10 for a perfect score and a grade 1 for an imperfect score. For example, in terms of the mass criteria, any UAV which had a system mass of 5 kg would be given a grade of 5. Systems with a lower mass would score higher and systems with a higher mass would score lower based on a non-linear relationship developed by the team through debate and referenced to Table 4 (see Figure 2a).

Figure 2 (a-i) – Criteria Selection Graphs.

The grades were then multiplied by the weighting factor and totalled to give a final aggregate mark. For this analysis, the <u>higher</u> the overall score, the <u>better</u> the system.

Tables 5a and 5b shows the UAV system specifications and the combined result for the top ten systems. These systems consist of Multiple Rotary Wing (6), Delta Wing (1), Tilt Rotor (1), Helicopter (1) and a Ducted Fan (1).

From this analysis the AirRobot [29] (Quadrotor System) came out top with a score of 520 points. For reference purposes, the perfect score would have been 840 points (clearly improvements can be made on this system). The Middlesex system following the PDS would have been awarded a score of 526 points following this assessment procedure; therefore the AirRobot system was very close in performance to the proposed Middlesex system.

In light of this result it was decided to submit a proposal to the MoD in May 2007 to purchase an AirRobot system and integrate it with the state-of-the-art MicroPilot MP2128^{HELI} Flight Control System from Canada as our competitive bid.

MicroPilot's Capabilities include airspeed hold, altitude hold, turn coordination, GPS navigation (1000 points), vertical takeoff and landing (VTOL), plus autonomous operation from launch to recovery. Included with MicroPilot's autopilot package is the Horizon ground control software. It offers a user-friendly point-and-click interface for mission planning, parameter adjustment, flight monitoring and mission simulation.

The Middlesex Co-Axial Tri-Rotor UAV (HALO)
The MoD GC entrants were informed in July 2007 of the result of the competitive bidding process. Our bid for Group 1 funding was unsuccessful. Out of the 23 bids submitted, the MoD had funded six (Group 1) teams (each being awarded approximately £300k) and had selected another eight (Group 2) teams to enter the competition unfunded [30].

Having reviewed the selection analysis table again we concluded that a multiple rotary winged UAV which had a VTOL capability could be a novel solution for MOUT. Having considered the options of a Quadrotor or a Tilt Rotor UAV, it was decided that a unique concept of Co-Axial Tri-Rotor would answer the MoD GC brief and provide a great deal of innovation since such a system did not currently exist. We named our UAV 'HALO™' due to its operational role of force protection.

After securing funding from internal research bids within the University, we began the process of prototyping, testing and the selection of COTS components.

The Co-Axial Drive Principle
Fundamental to the success of our chosen design is the co-axial drive unit, this consists of two props one mounted above the other rotating about the same axis in opposite directions and powered by separate motors. This arrangement allows the torque output of both units to be balanced thus negating the yaw moment whilst providing considerable thrust for a small package size (see Figure 3). Co-axial props have been used on a number of commercial aircraft including the British Supermarine Spitfire and the Russian Tupolev Tu-95 with great success. An excellent book describing the benefits of the co-axial arrangement, together with the momentum theory analysis is given by J. Gordon Leishman [31].

Figure 3 – The Co-Axial Drive Configuration and Thrust Capability.

After extensive testing with many different motor and propeller combinations, it was found that by using AXI 2217/20 outrunner motors combined with GWS 1060 (10" diameter x 6" pitch) 3-bladed propellers, each co-axial unit could produce a maximum Thrust of 19.6 N (2 kg) at 18 Amps (which is the Current capacity of the AXI motor) (see Figure 3).

Momentum Theory states that the Thrust, T of the propeller is proportional to the Rotational Speed, n^2 and the Diameter, D^4 of the propeller:

$$T = \rho \,.\, n^2 \,.\, D^4 \,.\, C_T \qquad [1]$$

Also the Power, P of the propeller is proportional to the Rotational Speed, n^3 and the Diameter, D^5 of the propeller:

$$P = \rho \,.\, n^3 \,.\, D^5 \,.\, C_P \qquad [2]$$

Where ρ = Density of Air 1.225 kg/m^3; C_T = Thrust Coefficient and Cp = Power Coefficient for a given propeller.

System Description
The HALO™ UAV therefore consists of a unique Co-Axial Tri-Rotor design (UK Patent Application GB0810886.2; Design Registration 4008525) which incorporates six AXI 2217/20 brushless outrunner motors, each capable of producing approx 5.6 N (570 g) of thrust at 7 Amps (6,200 RPM), connected to six GWS 1060 3-bladed props as can be seen in Figures 4(a-c) below.

Figure 4 - The original site model (a), CAD mock-up (b) and final design (c) of our proposed UAV system.

The mass of this UAV is 3.25 kg, which consists of a main system mass of 3.05 kg and an interchangeable payload of 0.2 kg. The system has the capability to increase this payload up to 2 kg if necessary depending on the required sensor package. The UAV is powered by 2 x 8,000 mAh, 14.8v Lithium-Polymer (Li-Po) batteries from MaxAmps in the US, which will draw a nominal current of 7 A per motor, making a total current draw per battery of 21 A. This will give a predicted minimum endurance of 23 mins, dependent on payload and environmental conditions. The team are also looking at other power sources including Hydrogen Fuel Cells.

The gross dimensions of the UAV are ∅0.7 m (tip to tip) x 0.3 m. The system is capable of hover and perch (it can land and still rotate its camera sensors). The maximum operating ceiling for the MoD GC 2008 was set at 120 m Above Ground Level (AGL) and the minimum operating ceiling was 20 m AGL thus avoiding human contact. However, the system can operate at any height, this being programmed by the operator at the mission planning level.

In terms of the Electro Optical (EO) payload, the system uses an interchangeable FLIR Photon 160, 6.3 mm, 8.3 Hz [32] Thermal Imaging (TI) camera with 5.8 GHz transmitter (1mW), together with a 6 Mp Pentax S60 stills camera mounted on gimbals (Yaw & Pitch ± 90°). A miniature wireless video camera (480 TV lines) with 5.8 GHz transmitter (1mW) is incorporated onto the UAV to enable real-time download of RGB video (forward view) to a laptop. A further miniature wireless video camera (310 TV lines) with 5.8 GHz transmitter (1mW) is mounted on the payload gimbal to enable a view of the stills camera prior to image capture. The miniature video cameras and transmitters typically weigh less than 25 g each.

Conclusion

The wars in Iraq and Afghanistan have been costly in both human and monetary terms; personnel and machines are wearing out and the political fallout from deaths of military servicemen and women cannot be underestimated. Unmanned Aircraft systems typically cost 1% of manned systems and can provide ISTAR in places where manned systems cannot go.

There is a requirement for small, lightweight and agile VTOL UAVs to be developed for use by a section or platoon sized military unit for MOUT, which at the present time remains unfulfilled. The UK MoD through its bold Defence Technology Strategy [33] has realised the need for a technological solution to the problems faced by our forces when operating in urban areas, and the MoD GC 2008 begins the process of answering this.

In conclusion, regardless of the outcome of the MoD GC 2008, Team i-Spy feel that this has been a tremendous learning curve and a great opportunity to compete in an industry dominated by the usual suspects. Given our relatively small manpower, experience and financial resources we believe that we have exceeded the MoD GC brief and created a unique platform which we hope will be further developed for use by the British Armed forces, where it will hopefully contribute to saving the lives of our service personnel.

Figure 5 – Mock-up of the HALO UAV in a Combat Situation.

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Table 1 – US, British and Civilian Casualties in Iraq and Afghanistan [3]

Country	Theatre	Dead	Wounded
US	Iraq	4,201	43,993
	Afghanistan	627	4,400†
	Total	**4,828**	**48,393†**
UK	Iraq	176	3,294*
	Afghanistan	125	1,970*
	Total	**301**	**5,264***
Civilian	Iraq	**97,094**	**N/A**
	Afghanistan	**10-30,000§**	**N/A**
	Total	**107-127,000**	**N/A**

† Estimated data based on known US casualty rates in Iraq.
** OP Telic and Herrick Casualty and Fatality Tables up to 15 Nov 2008 – MoD Factsheets.*
§ Estimates of civilian deaths range from 10,000 to 30,000 for the period 2001 to 2008.

Table 2 – Unmanned Aircraft System Categorization (Source: UAS Yearbook 2008-09)

UAS Categories	Acronym	Range (km)	Flight Altitude (m)	Endurance (hr)	MTOW (kg)
Tactical					
Nano	η	< 1	100	< 1	< 0.025
Micro	μ	< 10	250	1	< 5
Mini	MAV	< 10	150-300	< 2	< 30
Close Range	CR	10-30	3000	2-4	150
Short Range	SR	30-70	3000	3-6	200
Medium Range	MR	70-200	5000	6-10	1250
Medium Range Endurance	MRE	> 500	8000	10-16	1250
Low Altitude Deep Penetration	LADP	> 250	50-9000	0.5-1	350
Low Altitude Long Endurance	LALE	> 500	3000	> 24	< 30
Medium Altitude Long Endurance	MALE	> 500	14000	24-48	1500
Strategic					
High Altitude Long Endurance	HALE	> 2000	20000	24-48	4500
Special Purpose					
Unmanned Combat Aerial Vehicles	UCAV	1500	10000	2	10000
Lethal	LETH	300	4000	3-4	250
Decoy	DEC	0-500	5000	< 4	250
Stratospheric	STRATO	> 2000	20-30k	> 48	-

Table 3 - Overview of Viable UAV Options

Type	Low Cost	Availability	VTOL Capability	Small Size	Capable of Hover/Perch	High Payload Capacity	Simple Design	High Vertical Speed	High Horizontal Speed	Score
Fixed Wing	2	5	1	3	1	3	5	1	5	**26**
Rotary Wing (Helicopter)	2	4	5	2	5	4	2	4	3	**31**
Hybrid VTOL (Ducted Fan Design)	1	1	5	2	5	2	1	4	4	**25**
Blimp (Lighter-than-air Balloon)	4	3	5	1	5	1	5	1	1	**26**
Ornithopter (Flapping Wings)	3	1	5	4	3	1	5	2	2	**26**
Dropped (Para-glider)	4	1	1	3	1	4	4	3	4	**25**
Launched (Rocket, Pressurised gas, Slingshot)	3	3	4	4	1	2	5	5	1	**28**

Scale: 1 = Highly Disagree; 2 = Disagree; 3 = Neutral; 4 = Agree; 5 = Highly Agree

Max Possible Score = 45
Min Possible Score = 9

Table 4 – Selection Criteria & Associated Weightings

Weighting	Criteria	Quantative or Qualitative	Unit	Less	Value or Range	More	
10	*Mass*	*Quantitative*	*kg*	++	*5*	--	*Ability to be carried over long distances by an infantry soldier.*
10	*Payload*	*Quantitative*	*kg*	--	*2*	+	*Ability to provide sensor capability, such as video, thermal, etc.*
9	*Manoeuvrability*	*Quantitative*	*DoF*	--	*4*	+	*Ability to manoeuver in tight spaces, enter doorways, windows, etc.*
9	*Speed*	*Quantitative*	*m/s*	++	*0 to 3*	-	*Ability to hover is very important.*
8	*Volume*	*Quantitative*	*m*	++	*0.35 x 0.45 x 0.3*	--	*Ability to be carried in a standard infantry PLCE 80lt backpack.*
7	*Set-Up Time*	*Quantitative*	*mins*	++	*5*	-	*Ability to be set-up and operational in minimum time.*
10	*Endurance*	*Quantitative*	*mins*	--	*30-60*	-	*Ability to be able to operate for 60 minutes.*
8	*Concealment*	Both	*db(A)*	++	*60 @ 3 m*	--	*Invisible via small size, camouflage and noise.*
6	*Survivability*	Qualitative	*N/A*	--	*N/A*	++	*Ability to survive against weather conditions, accidental collision and offensive weapons.*
7	*Unit Cost*	Quantitative	*£*	++	*5000*	-	*Ability to provide each platoon with at least one unit.*

++	*Very good*
+	*Good*
	Neutral
-	*Bad*
--	*Very bad*

Table 5a – Top Ten Systems Specifications Sheet

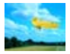
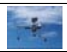
Classification	Image	Name	Ctry	Website/Company (URL)	Price (£)	Mass (kg)	Payload (kg)	Wingspan (m)/Size (m)	Endurance (mins)	Ceiling (m)	Speed (m/s)	Range (Km)	Weighted Scores	Notes
Multiple Rotary Wing		AirRobot	GER	www.airrobot.com	20,000	1	0.2	1.0 x 0.2	30	500	0 to 11	6	***520***	Thermal Imaging Camera avaliable
Helicopter		Comet 500 Helicopter	US	http://www.theflyingmachines.com/comet500_premium.php	500	0.39	0.15	0.66 x 0.23 x 0.12	20	700	0 to 18	21	***516***	
Delta Wing		Mosquito	ISR	http://www.iai.co.il/Default.aspx?docID=34525&FolderID=3373	25,000	0.5	0.15	0.3	40	90	13	32	***506***	
Multiple Rotary Wing		Draganflyer X-Pro	US	http://www.rctoys.com/rc-toys-and-parts/DF-XPRO/INDUSTRIAL.html	3,000	2.5	0.45	0.88 x 0.88	18	500	0 to 18	3	***504***	
Tilt Rotor		OVIWUN Unmanned Air Vehicle (UAV)	US	http://www.trekaero.com/Trek_VTOL_OVIWUN_Vehicles.htm	7,500	2.53	3	0.65 x 0.41 x 0.36	20	1676	0 to 20	4	***501***	
Multiple Rotary Wing		Silverlit RC UFO Helicopter	US	http://www.hobbytron.com/SilverLit-X-UFO-RC-Flying-Machine	150	0.322	0.15	0.59 x 0.59 x 0.06	20	10	0 to 2	0.1	***496***	
Multiple Rotary Wing		Draganflyer SAVS Stabilized Aerial Video System	US	http://www.rctoys.com/rc-toys-and-parts/DF-SAVS/INDUSTRI	1,200	0.5	0.05	0.76 x 0.76	12-15	500	0 to 9	3	***488***	Camera Payload avaliable
Multiple Rotary Wing		Fancopter	GER	www.emt-penzberg.de	65,000	1.3	0.3	0.65 x 0.4	20	1000	0 to 14	0.5	***476***	Thermal Imaging Camera avaliable
Ducted Fan		AAI Corp MAV joined with Honeywell	US	http://www.aaicorp.com/New/UAS/html/mav.html	125,000	6	1.6	0.3 x 0.3 x 0.5	40	3,200	0 to 26	62	***468***	Flight Tests Dec 2008
Multiple Rotary Wing		Microdrone MD200	GER	http://www.microdrones.com/	20,000	0.9	0.2	0.7	20	700	0 to 15	4	***438***	Capability to carry a Digital Camera

Table 5b - Selection Table Showing the Final Result

Classification	***Name***	***Mass***	***Payload***	***Manoeuvrabillity***	***Speed (max/min)***	***Volume***	***Set-up Time***	***Endurance***	***Concealment***	***Survivabillity***	***Unit Cost***	***Weighted Total***
		10	10	9	9	8	7	10	8	6	7	
Multiple Rotary Wing	***AirRobot***	10	2	8	10	1	5	10	5	8	1	***520***
Helicopter	*Comet 500 Helicopter*	10	1	8	10	6	5	6	4	1	9	***516***
Delta Wing	*Mosquito*	10	1	5	2	8	8	10	8	7	1	***506***
Multiple Rotary Wing	*Draganflyer X-Pro*	9	4	8	10	4	5	5	5	1	7	***504***
Tilt Rotor	*OVIWUN Unmanned Air Vehicle (UAV)*	9	6	8	10	1	3	6	3	8	4	***501***
Multiple Rotary Wing	*Silverlit RC UFO Helicopter*	10	1	8	7	5	5	6	5	1	10	***496***
Multiple Rotary Wing	*Draganflyer SAVS Stabilized Aerial Video System*	10	1	8	10	4	5	4	5	1	9	***488***
Multiple Rotary Wing	*FanCopter*	10	3	8	10	1	3	6	5	8	1	***476***
Ducted Fan	*AAI Corp MAV joined with Honeywell*	3	6	8	10	1	3	10	4	8	1	***468***
Multiple Rotary Wing	*Micro Drone MD 200*	10	2	8	10	1	5	6	5	1	1	***438***
	MDX Spec	5	*6*	*8*	*10*	*1*	*5*	*10*	*5*	*6*	*5*	***526***
	Perfect Score	10	*10*	*10*	*10*	*10*	*10*	*10*	*10*	*10*	*10*	***840***

Figure 1 – Examples of Nano [12], Micro [13] and Mini [14] UAVs.

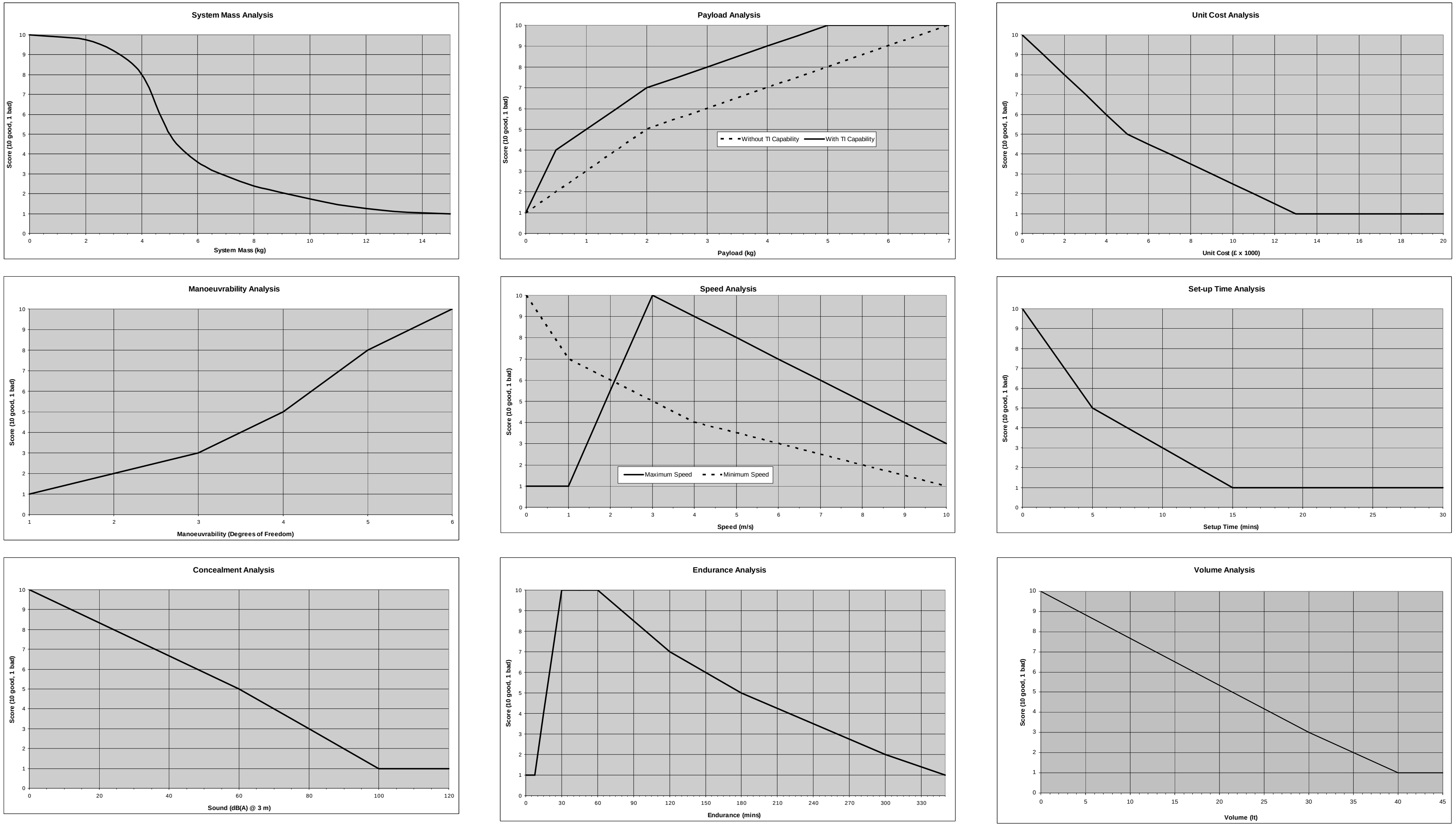


Figure 2 (a-i) – Criteria Selection Graphs.

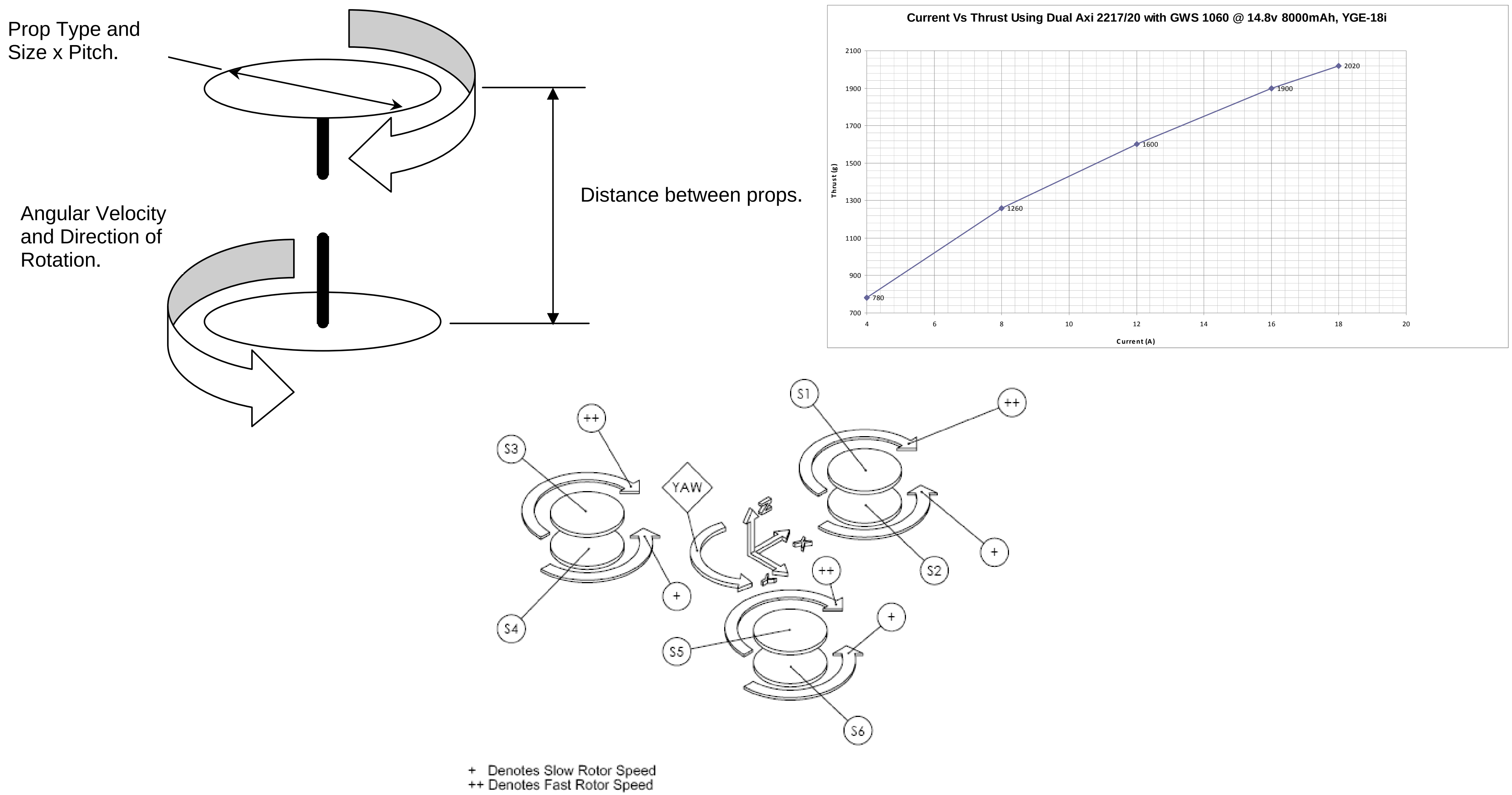
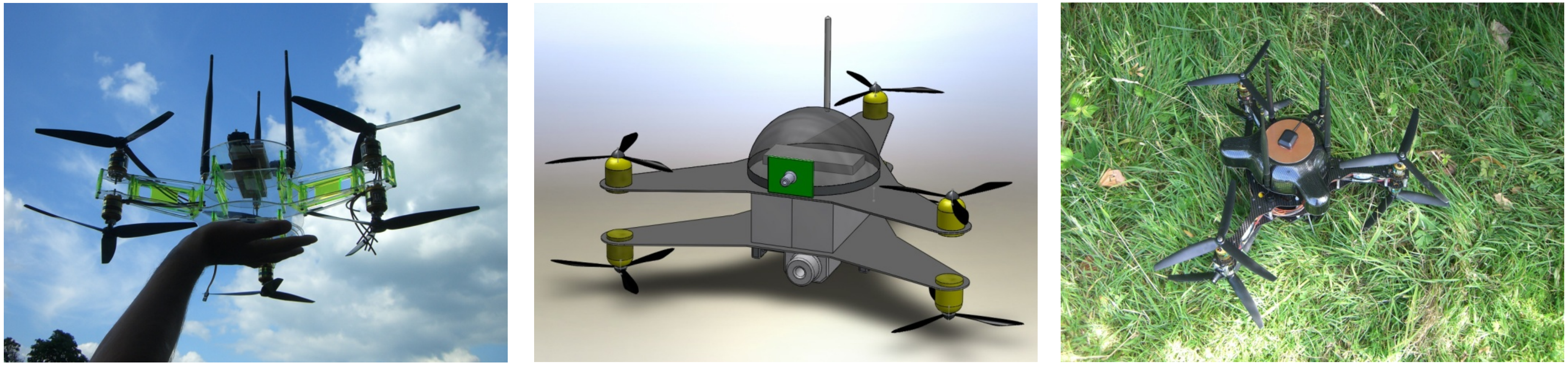


Figure 3 - The Co-Axial Drive Configuration and Thrust Capability.



(a) **(b)** **(c)**

Figure 4 - The original site model (a), CAD mock-up (b) and final design (c) of our prototype HALO UAV system.

Figure 5 – Mock-up of the HALO UAV in a Combat Scenario.