

Design and fabrication of a micro-class unmanned aerial vehicle (UAV) with high payload fraction

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ABSTRACT

Unmanned aerial vehicle industry is highly charismatic and constantly expanding with the growth of science and technology in the context of Bangladesh. This paper presents the design and fabrication of a micro-class UAV, capable to take maximum payload with minimum empty weight. The iterative process of design is to meet the specific requirements set by the Society of Automotive Engineers, USA for their annual international aero-design competition. The preliminary and detailed design required optimization process and trade-study, material selection, propulsion system integration, electrical system design, control system design, analysis of aerodynamics characteristics as well as determining stability and control parameters. Finally, wind tunnel tests were carried out before flight test under real flight situation to analyze the performance parameters and subsequent modification was done to turn the UAV into a desired one incorporating all necessary design requirements. The self-weight of the designed UAV was only 450 grams and it lifted another 890 grams of payload; the high payload fraction clinched 4th position out of 33 teams from different Universities of the world.

Keywords: UAV design, aerodynamics, stability and control, multi-disciplinary optimization, trade-study.

1. Introduction

Society of Automotive Engineers (SAE), USA has been organizing SAE Aero-Design Competition among the Universities of the World since 1986. Design and fabrication of the unmanned aerial vehicle (UAV) presented in this paper started with the aim of participating in SAE Aero-Design Competition 2014 with the specific objective of maximizing the payload fraction. Payload fraction is the ratio of the weight of the external load that the UAV carries to the total weight of the UAV. Maximizing the payload fraction requires blending the knowledge on aerodynamics, aero-structure, stability and control, strength of materials and multi-disciplinary optimization.

The design process was started with the conceptual design, where all the basic aspects like configuration, power-plant, wing, empennage and fuselage were designed. A trade study analysis ensured that the selected value of wing loading and power to weight ratio will lead to the maximum payload fraction. Detailed design was carried out basing on the frozen design and parts and subsystems were fabricated. Lastly, flight tests were carried out and further modifications were incorporated before fabricating the final version of the UAV.

2. Conceptual design

Configuration was chosen on the basis of sensitivity analysis which determined how well the UAV could accomplish the task of the mission. Wing and tail configuration, propulsion system, payload location were picked from few possible options as described below.

2.1 Wing configuration

Wing configuration was chosen on the basis of empty weight, maneuverability, aerodynamics, stability,

manufacturability and payload integration and it was found that conventional configuration with high wing location would be the optimum option [1]. The idea of using low-wing would not be viable as it would create problem during landing (as designed UAV will not have any landing gear). A mid-wing is quite difficult to build an UAV due to its carry-through characteristics as well as the difficulty to provide the required taper ratio. So, a high wing was the most suitable option for this UAV. In addition, a high wing will tend to give some degree of dihedral at the time of flight as it carries the overall payload in the middle and lift is generated from the wing; such dihedral increases rolling stability and works against any perturbation appearing from gust wind or any other environmental disturbance during actual flight.

2.2 Tail configuration

Among the available options of tail configuration, the option of T-tail was not considered because of its being heavier than conventional tail [1] and requirement of additional strength of the empennage. V-tail was another option as it reduces wetted area, but it gives adverse maneuverability which causes great difficulties for the controls engineer to design effectively how the control surfaces of the UAV would behave. Finally, considering system weight, stability and control, landing and take-off, drag and ease in manufacturing, conventional tail was considered as the best option for the UAV under design.

2.3 Propulsion system integration

In order to keep the system simple, a battery pack and propeller configuration was found to be the most suitable for this UAV. Considering system weight, power to weight ratio, and effect on stability and controllability, this UAV was decided to be fitted with

single tractor propulsion system. Because of being small aircraft, corkscrew effect wouldn't affect this design.

2.4 Payload location

Payload location was preferred inside the fuselage to lessen drag, ease of launch and elementary manufacturability. If the payload were positioned outside the fuselage, it would cause additional drag and if the payload were hung with sling, it would be difficult to accurately position the CG position, which is vital for stability and controllability analysis. In addition, the payload bay was designed in such a way that the location of the CG can be slightly changed as per the requirement of stability basing on the atmospheric condition and associated disturbances.

3. Preliminary design

Successive iterative procedure was adopted for important design parameters and multi-disciplinary optimization was implemented during preliminary design phase to reach to highest payload fraction. Minimizing empty weight and increasing lifting capability as well as maximum capability of carrying payload with minimum weight became the driving motive of all the design phases and sizing trade-offs.

3.1 Airfoil selection

With a view to increase the performance, 'aerodynamic twist' was introduced using two different airfoils: Eppler 214 at the root and Selig 1223 at the tip of the planform. Such combination was chosen to ensure the desired stall characteristics of the UAV. By conducting the wind tunnel test of the modified airfoil, it was seen that the combination airfoil provided optimum values of maximum lift coefficient ($C_{L,max}$), zero lift drag coefficient ($C_{D,0}$), max thickness (t_{max}/c), pitching moment coefficient (C_M), maximum value of C_L/C_D and stalling characteristics. The maximum lift coefficient for this modified airfoil came out to be 2.044.

3.2 Motor and propeller optimization

As in case of motor-driven remote-controlled aircraft, propeller pitch and diameter are related to motor power, motor power was optimized first and propeller specifications were set accordingly. On the basis of the experimental performances of three different motors, EMAX BL CF2822 was proved to be the most optimum.

3.3 Battery, Electronic Speed Controller (ESC) and Servo motor optimization

Among the components of the propulsive system, battery is the power supplier. With the increment in battery cell, power generation increases along with a significant increase in battery weight. So, an 850 mAh 3-cell (11.1V) battery was selected which provided sufficient power to drive the motor having an acceptable self-weight. Matching with the motor specifications, a 20A Electronic Speed Controller (ESC) was selected to feed the power from battery to motor.

4. Detailed design

During detailed design, the testing effort intensified and the actual structure of the aircraft was fabricated and tested. The important part was the production design to enter the full scale development.

4.1 Design features and details

Optimization was done for the wing and empennage planforms. Finally, rectangular main wing was designed with chord length, span, area and aspect ratio of 6.5 in, 38 in, 247 sq in and 5.85 respectively. On the other hand, a flat plate horizontal stabilizer with chord length of 4 in, span of 12.5 in, area of 50 sq in and aspect ratio of 3.1 were used while vertical stabilizer had height of 5.8 in, root chord of 5.8 in and tip chord of 2.3 in. Finally the length, width, height and gross weight of the complete airplane were 23.5 in, 38 in, 5.8 in and 329 g respectively.

4.2 Weight build up and structural characteristics

Component wise weights were calculated; weight build-up pie chart is shown in Fig.1. In addition to the structural materials, 33 gm weight was added due to connecting rod for wing, binding tape and the rubber band used for attaching wing with the fuselage. Reducing the empty weight was the prime motive in the entire design process. The loads acting at each prominent load bearing members were calculated and a factor of safety of 1.25 was used. The low factor of safety and exact calculation of stress ensured that material is not added unnecessarily, which will provide the capability of carrying highest payload by the designed airplane.

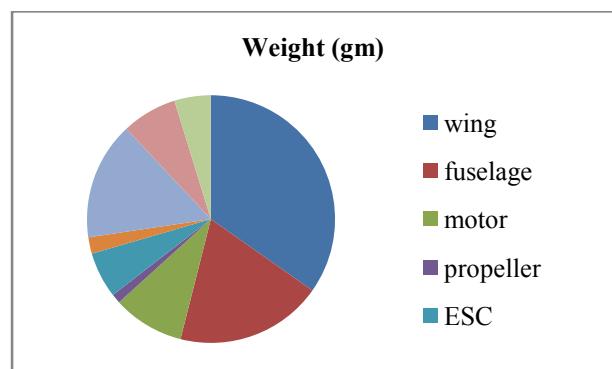


Fig.1 Weight build-up of the designed UAV.

4.3 Wing and empennage design

Aerodynamic twist was used in the wing. By using two separate airfoils, E214 at root and S1223 at the tip, the angle between the zero-lift angle of tip airfoil and the zero-lift angle of the root airfoil were different and such twisting was incorporated to reshape the lift distribution favorably. Between root and tip chord, the airfoils were meshed up while 6.5" chord and 38" span were used to keep the aspect ratio low as well as high lift. Theoretically this wing can carry a payload, which is 3 times the empty weight of the entire aircraft.

Conventional tail was selected in the empennage because it is easier to construct, can recover from wing drag although less effective for pitch stability at high α . However, the prime concern was to reduce the empty weight, so despite lower effectiveness at high angle of attack, conventional configuration was chosen. Flat plate was used at the empennage design which was constructed by foam sheet.

4.4 Materials used

To keep the weight low, solid foam was used in wing fabrication. To give the wing sufficient strength, it was covered with glue and later with covering paper. The covering paper was provided with heat treatment to increase strength and provide aerodynamic shape.

4.5 Electronics design and flight performance parameters

Two ailerons were controlled by two different servomotors while rudder and elevator were controlled by separate servomotor. Servo mechanism is a control system that converts a small mechanical motion into one requiring much greater power. Metal gear servos were used for greater torque and less weight factor.

5. Analysis

With all the components of the UAV, finally the wing loading, gross weight and stall speed came out to be 33.33 oz/ft², 1130 gm and 9.03 m/s. For further analysis, either Computational Fluid Dynamics (CFD) or Experimental Fluid Dynamics needed to be used. CFD analysis gives a computational result of the design while wind tunnel testing gives experimental results. Although, CFD analysis before the actual fabrication would be desirable, such simulation could not be carried out due to the non-availability of large computational resource. Wind tunnel testing was carried out to determine the behavior of the wing with aerodynamic twist.



Fig.2 Experimenting the modified wing in wind tunnel.

5.1 Aerodynamic Drag Determination

Drag of UAV is calculated at Reynolds's Number of 1.5657×10^5 [5]. Component wise drag build up and UAV drag prediction is shown in Table 1.

Table 1 Data for drag build up.

Component	C_{D0}	% of total drag
Wing	0.00605	55%
Fuselage	0.00275	25%
Vertical stabilizer	0.00110	10%
Horizontal stabilizer	0.00055	6%
Motor	0.00044	4%
Total	0.0110	100%

50% of the total thrust was sufficient to produce the necessary lift for taking off without runway as it can be launched by hand. Instead of using landing gear the structure of the body was developed in such a way that it could withstand the shock it receives while landing and is able to perform necessary maneuvering which is required. To avoid the downwash effect, the concept of Aerodynamic Twist was developed such as an airfoil (selig-1223) was kept at the tip which could produce more lift while flying and then another airfoil with comparatively less lifting coefficient (Eppler-214) at the root of the wing. A bit dihedral wing was used for performance flight to make it stable and increase the weight lifting capabilities. Because of its small size, the aero elasticity effect was not that significant on the UAV, though some aero elastic effects affected the wing while performing the flight tests which caused the wings to bend 3-4 inches.

5.2 Stability analysis

The UAV was designed with the aim of positive longitudinal stability. As the stabilizer is placed aft of CG, it facilitates built in stability. The contribution of the wing was destabilizing while the contribution of the fuselage was mildly destabilizing. The tail size was calculated using tail volume coefficient method so that the desired degree of positive longitudinal stability is ensured. Using the techniques of Roskam and Etkin, stability and control derivatives were calculated, as shown in Fig. 3 while these values were confirmed through AVL.

Angle of Attack					
$CL\alpha$			5.40		
$CM\alpha$			-0.50		
$Cy\beta$	-0.30	$Cy\dot{\beta}$	-0.07	$Cy\gamma$	0.30
$Cz\beta$	-0.03	$Cz\dot{\beta}$	-0.49	$Cz\gamma$	+0.27
$Cn\beta$	0.02	$Cn\dot{\beta}$	0.0035	$Cn\gamma$	-0.17
Pitch Rate		Aileron Deflection δ_a		Elevator Deflection δ_e	
$CL\alpha$	5.75	$Cl_{\alpha\delta_a}$	0.006	$CL\delta_e$	0.0059
$CM\alpha$	-4.5	$Cm_{\alpha\delta_a}$	0.0003	$Cm\delta_e$	-0.014

Fig.3 Stability derivatives

5.3 Weight and balance

Dividing the parts of aircraft with the help of Fig.4, the following Table 2 shows the weight, moment-arm and momentum of each sub-assembly. Finally the CG of the UAV was found to be located at a distance of 8.57 in from the nose [5].

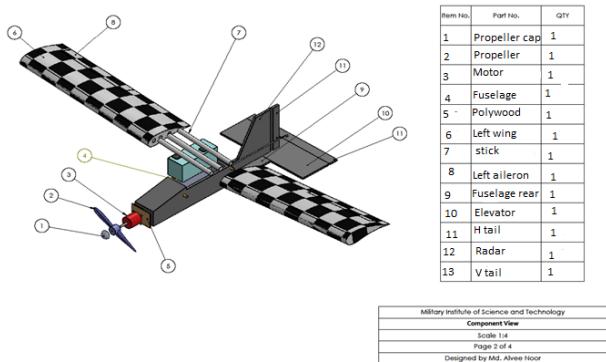


Fig.4 Calculating location of CG

Table 2 Calculation of CG location

Component	Weight(lb)	Arm length(in)	Momentum (in-lb)
Fuselage1	0.183	2.33	0.426
Fuselage2	0.068	9.75	0.663
Fuselage3	0.439	14.5	6.366
Fuselage4	0.070	19.2	1.344
Wing	0.242	8.16	1.970
V tail1	0.033	19.00	0.627
V tail2	0.066	21.25	1.403
V tail3	0.067	23.00	1.541
H tail	0.432	22.90	9.893
ESC	0.048	4.75	0.228
Receiver	0.031	10.43	0.321
Servo	0.066	12.00	0.792
Motor	0.086	1.75	0.150
Propeller	0.011	0.50	0.005
Battery	0.141	8.05	1.136
Others	1.653	2.60	4.298
Total	3.636	-	31.163

5 Testing plan

The entire UAV along with the propulsion system was tested to observe how the component works together and to determine the systems performance parameters such as thrust, torque, RPM, current, voltage at different airspeeds. Again the entire propulsion system was also tested with various types of propellers which enabled the verification of propeller optimization process. Voltage drop and the actual usable capacities were the critical performance variable in the case of battery testing. Propeller with various diameters and pitch angle were tested in a wind tunnel with the help of a constant power source and motor which helped to optimize the thrust and RPM. To check whether the material used in the UAV will be able to withstand various loads during flying or not, the bending test was

conducted for the wing. The ultimate validation of the design was done through numerous flight tests.

6 Manufacturing plan and process

To conserve weight, multiple manufacturing methods were considered. Emphasis was given not only to provide a large internal area close to the CG for storing the payload and flight systems internally but also to ensure that the structure was strong and durable enough to possess dimensional accuracy over the integrated airframe. Finally, during the fabrication of the parts of the UAV, it was carefully handled in such a manner so that the whole UAV can be assembled within the time limit prescribed by SAE.

6.1 Materials selection

Careful material selection is an inescapable requirement for a good UAV as it strongly affects the design criteria of having less empty weight. Solid foam was used to construct the wing in order to get an ice shape of the airfoil as well as to gain structural strength and it can be machined easily also. Balsa wood is a very light weight wood which was used during the wing fabrication. Though it is pretty expensive, it was used for more strength as well as to keep the empty weight of the aircraft as low as possible. Foam sheet was the main material which has been used for manufacturing the UAV and these are very much ductile which allows it to absorb the shock while landing. High density foam "XPS" was used to mount the motor with the fuselage because this has the ability to sustain high vibration as well as to provide necessary strength for holding the motor. Heat was provided to fix the covering material with the wing which was used in order to cover the wing as well as to give it more strength. Fiber tape was used in order to get more strength in the joints. Thus the materials selection was done carefully so that they can provide enough strength to withstand the load imposed on it.

6.2 Subsystem manufacturing

6.2.1 Wing manufacturing

Mainly solid foam and Balsa wood were used for manufacturing the wing. First the dimensions of the wing were selected. A high lift airfoil was placed at the tip of the wing and comparatively low-lift airfoil was fixed at the root. While fabricating the wing, hotwire was used to cut the foam at the desired shape. Later on after sanding, glue was applied over the whole wing. Then the covering material was applied using some heat.

6.2.2 Fuselage manufacturing

At first a design was selected for the fuselage and gave it dimensions. Then a suitable material (Foam sheet) was selected which can meet the requirements. Different parts of the UAV were fabricated and later on assembled using adhesives. Housings were also made for each and every part of the aircraft for a stable CG point.

6.2.3 Empennage manufacturing

Firstly a suitable configuration of the empennage was selected for the UAV. Flat plate was used instead of using an airfoil shaped surface because of ease of fabrication and simplicity without affecting the performance in case of such a small UAV. A special type of adhesive (Epoxy Resin) was used for assembling the parts for better strength. This adhesive provided high strength and it has some ductility property as well.

7. Novel idea exploited in the design

The primary concern was to obtain a high payload fraction by increasing the lift per unit area as much as possible. While lift is given by

$$L = \frac{1}{2} \rho v^2 S C_L \quad (1)$$

where ρ (density) was considered constant due to low variation in flight altitude, S (wing area) remained constant due to design constraints and considering the aircraft to be flown at max power, the velocity was also considered constant as well, the only option available was to choose an airfoil with very high C_L with maximum optimization without compromising the stalling pattern. The two airfoils that were considered are discussed below.

7.1 Eppler 214

Eppler 214 was chosen first due to its thickness and cambered surface. The max C_L obtained by the airfoil was determined to be $C_L=1.549$ at an AOA of 9° . Any further increase in AOA caused stall to the aircraft. The associated C_D was determined to be $C_D=0.0327$. The weight lifted by a wing of calculated size using this airfoil was approximately 1.5 lbs.

7.2 Selig 1223

Selig 1223 was further chosen in order to increase the capability of lifting weight. It was chosen for the high C_L and cambered surface. The max C_L obtained by the airfoil was determined to be $C_L=2.425$ at an AOA of 8° . Any further increase in AOA caused stall to the aircraft. The associated C_D was determined to be $C_D=0.0371$. The weight lifted by a wing of calculated size using this airfoil was approximately 2 lbs.

7.3 Aerodynamic twist

Both the airfoils were integrated in the designed aircraft in order to obtain a better and optimum result. The Selig 1223 airfoil was kept at the tip and the Eppler214 was kept at the tip of the wing. The stalling of Selig 1223 takes place earlier and the stalling of Eppler214 at root took place later. Initiation of the stall from the tip causes a juddering in the tail plane and sends an indication of upcoming stall of the whole aircraft and the UAV controller can take preventive action accordingly. In addition, the novel idea of aerodynamic twist introduced in our design increased the lift coefficient and reduced the drag coefficient, which was found from the flight

tests. The amount of weight lifted by the aircraft with the customized wing was approximately 3 lbs.

8. Performance in the actual competition

The designed and fabricated UAV was flown in the final competition of SAE Aero Design Competition (West) at Texas, USA from 28-30 March 2014. The UAV successfully took-off with the payload of 1.85 lbs while the empty weight of the UAV was only 0.99 lbs. Thus, the payload fraction was $1.85/(1.85+0.99) = 0.65$, which was the 4th best payload fraction among the 25 teams participating from renowned Universities of the World. The details of the participating teams and payload fraction of each UAV are shown in Fig.5. Mentionable that, this is the best achievement and highest positioning by any team from Bangladesh till now in any International Aero Design Competition.

9 Conclusions

The design process was started with the conceptual design, where the ideas of every aspect of aircraft design were contemplated and evaluated including overall configuration, wing and tail configuration, fuselage type and payload storage. Hand launch system was incorporated instead of landing gears for easy take-off and reduction of empty weight as payload fraction was the main concern. From the back-of-the-napkin design, propulsion system, airfoil and wing, wing/body plan form and other structural aspects were designed and analyzed while multi-disciplinary optimization was the heart of the trade-off study. Finalizing the detailed design with every individual configuration, it was seen that the aircraft generates an ample amount of lift with the help of two different airfoils known as "Aerodynamic Twist". The propulsion system such as battery, motor, ESC and others were chosen to work with the lowest possible weight and the lightest possible combination of structure to support a strong and dynamically stable aircraft. Finally extensive flight testing in addition to comprehensive wind tunnel testing confirmed the desired performance capabilities. The ultimate output of the design was the successful flight of the UAV in the skies of USA and clinching 4th position out of 25 teams in payload fraction category, which is the best result by any Bangladeshi UAV till now.

NOMENCLATURE

R_n	Round score
P_n	Payloads
PF_n	Payload fraction
C_l	Lift coefficient
C_d	Drag coefficient
$\frac{t}{c}$	Thickness to chord ratio
$\frac{Cl}{Cd}$	Lift to drag ratio
C_{D0}	Zero lift drag co-efficient
α	Angle of attack
C_{La}	R/C of lift coefficient with angle of attack
C_{Ma}	R/C of pitching moment coefficient with AOA

SAE: 2014 Aero Design West (Fort Worth, TX)

Micro Class Payload Fraction

Pos.	No.	Country	School	Team Name	Best Payload Fraction
1	319	Canada	Univ of Western Ontario	Western Aero Design - Micro	0.8121
2	310	Poland	Polish Air Force Academy in Dyblin	Young Engineers Team-ArrowPro	0.8016
3	324	Poland	Wroclaw University of Technology	JetStream	0.7634
4	315	Bangladesh	Military Inst of Science & Technology	MIST Aero Thunder Green	0.6526
5	330	India	Indian Institute of Tech - Kanpur	Team Pushpak	0.6445
6	317	India	M M Engineering University	VIVAN	0.5904
7	303	India	Vellore Institute of Technology	VIMAANAS	0.5634
8	322	India	PES School of Engineering	Avions	0.5625
9	327	United States	Louisiana State Univ	Flying Tigers	0.5328
10	328	India	PES Institute of Technology	Icarus	0.5294
11	326	Turkey	Anadolu Universitesi	Flying Anatolia	0.5080
12	314	United States	Univ of Hawaii - Manoa	UH MICRO Warriors	0.4991
13	302	Turkey	Middle East Technical Univ	Owl Tamers	0.4918
14	329	India	BMS College of Engineering	Team Mach	0.4621
15	325	India	Hindustan University	GARUDA	0.3780
16	312	India	KIIT University	KIIT AERO	0.3268
17	320	India	M.H. Saboo Siddik College of Engrg	Team Aerosouls Micro	0.0000
18	308	United States	Saint Louis Univ	Parks Micro	0.0000
19	311	India	Sona College of Technology	TEAM DANPHE	0.0000
20	331	India	SRM University - NCR Campus	ONE	0.0000
21	313	United States	Univ of Nevada - Las Vegas	Rebel Recon	0.0000
22	321	India	Fr Conceicao Rodrigues College of Engrg	Team Vaayushastra Micro Class	0.0000
23	318	India	Manipal Institute of Tech	AeroMIT	0.0000
24	305	Canada	Queen's Univ - Ontario Canada	Queen's Eh	0.0000
25	323	United States	Wright State Univ	Flyboys	0.0000

Fig.5 Final result in flying (payload fraction) at SAE Aero Design Competition, Texas, USA from 28-30 March 2014.

C_{yb}	R/C of side force coefficient with yaw angle
C_{lb}	Rate of change of rolling moment coefficient with yaw angle
C_{nb}	R/c of yawing moment coefficient with yaw angle
C_{yp}	R/C of side force coefficient with roll rate
C_{lp}	R/C of rolling moment coefficient with roll rate
C_{np}	R/C of yawing moment coefficient with roll rate
C_{yr}	R/C of side force coefficient with yaw rate
C_{lr}	R/C of rolling moment coefficient with yaw rate
C_{nr}	R/C of yawing moment coefficient with yaw rate
C_{lq}	R/C of rolling moment coefficient with pitch rate
C_{mq}	R/C of pitching moment coefficient with pitch rate
$C_{L\delta a}$	R/C of Lift coefficient with aileron deflection
$C_{M\delta a}$	R/C of Pitching Moment coefficient with aileron deflection
$C_{L\delta e}$	R/C of Lift coefficient with elevator deflection

$C_{M\delta e}$	R/C of Pitching Moment coefficient with elevator deflection
$C_{L\delta f}$	R/C of Lift coefficient with flap deflection
$C_{M\delta f}$	R/C of Pitching Moment coefficient with flap deflection

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