Airfoil Selection, Optimization and Analysis for a Solar-Powered Unmanned Aerial Vehicles

Avinash Kini Mattar
R.V.College of Engineering
Bangalore, Karnataka, India
+91 95359 25701
kiniavinash@gmail.com

Chetan Vaidya
R.V.College of Engineering
Bangalore, Karnataka, India
+91 94819 04574
chetanv23@gmail.com

Anirudh Mukund Saraf
R.V.College of Engineering
Bangalore, Karnataka, India
+91 96320 08705
anirudh.m.saraf@gmail.com

Abstract— **This paper presents a method for obtaining an optimal airfoil for a Solar-powered Unmanned Aerial Vehicle (UAV). This method uses B-spline shape functions along with control points to define the geometry of the airfoil and Pattern Search (PS) optimization algorithm to obtain the optimal airfoil for the UAV from a given initial vector. The wing of the UAV was considered to operate at Reynolds Number of $2x10^5$. Hence, existing airfoils from a low Reynolds Number airfoil database [7] which performed the best at the considered Reynolds Number were selected and interpolated together in XFLR5 to obtain the initial vector. An XFOIL-MATLAB interface was built for the evaluation of the aerodynamic performance of each generated airfoil during the optimisation process. The conditions of evaluation were Reynolds Number = $2x10^5$, Angle of Attack ranging from -5^0 to 12^0. The objective function for the optimisation algorithm includes the lift-drag characteristics of an airfoil in order to optimise glide and range and also minimise power consumption in the operating angle of attack of the UAV. This operating range varies from angles -2^0 to 4^0 during different phases of the flight. Constraints for the program includes manufacturing feasibility of the wing with solar panels for which penalty is included in the objective function. Due to limited flexibility of the solar panels, the curvature limitation on the suction surface of the airfoil, towards its trailing edge, is taken into account by placing limited number of control points in that area [2] and having a restriction on the degrees of freedom of the same. The resulting airfoil has an average of 13.93% increase C_L/C_D and 15.21% increase in ${C_L}^{1.5}/C_D$ compared to the selected initial airfoil.**

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1. INTRODUCTION

The use of renewable energy technology is on the rise. With depleting fossil fuel reserves and deterioration of the environment, the use of renewable energy is eventually inevitable across all domains of technology. With solar energy being the most abundant renewable energy resource on the Earth, the motivation behind the paper is to facilitate the introduction of solar energy technology into the domain of Unmanned Aerial Vehicles (UAV). Currently, UAVs use electric battery technology or fuel-based propulsion systems. Their endurance i.e time of flight, however, is limited by the number of batteries or amount of fuel that they can carry. Incorporating solar energy technology has the potential for infinite endurance UAV.

The placement of solar panels is one of the key factors to the overall design process of solar powered UAV. Since, majority of the panels is to be placed on the wing, it could compromise its cross-sectional shape (airfoil) and thus its performance. Hence, during process of airfoil selection and design, panel flexibility limitation and the extent of curvature of the suction side of the airfoil should be taken into consideration. Therefore, airfoil design is very crucial to the performance of the UAV.

Airfoil design methods can be classified into two categories: Direct design and Inverse design. Direct design involves computing and evaluating the pressure distribution over an airfoil section and at specified conditions (angle of attack, Reynolds number, Mach number), whereas in Inverse design, the shape of the airfoil is determined by defining the surface flow conditions at specified operating point. This paper employs direct design approach to generate and optimize airfoil shapes.

The paper presents a method wherein an airfoil is obtained by using optimization algorithm to search through the pre-defined geometrical limits. To evaluate the aerodynamic performance of each intermediate generated airfoil, a program called XFOIL is used. It is an interactive program for the design and analysis of subsonic isolated airfoils. Given the coordinates specifying the shape of a 2-D airfoil, Reynolds and Mach numbers, XFOIL can calculate the pressure distribution on the airfoil and hence lift and drag characteristics. The Optimization algorithm is implemented

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on MATLAB. It is a high-performance language for technical computing. An interface for XFOIL-MATLAB is built to evaluate the airfoil and access its polars. The optimization algorithm, the interface function used are described in the subsequent sections and the properties of the objective function are discussed. XFLR5 is an analysis tool for airfoils, wings and planes operating at low Reynolds Numbers.

2. METHOD DESCRIPTION

The figure 1 depicts the flow of the optimisation process. Airfoils are generated and parameterised using the B-spline method. The optimisation algorithm takes a user-supplied start-point. With the help of control points of the B-spline, airfoil geometry is continuously modified and analysed to get an optimal airfoil.

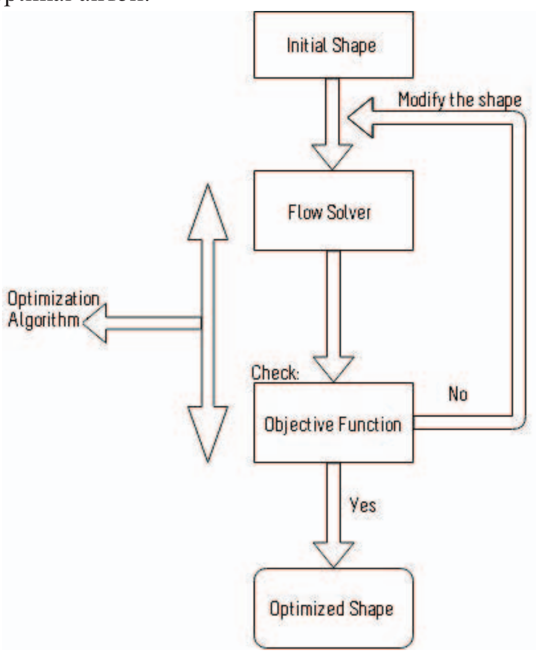

Figure 1: Flowchart of the process described

3. AIRFOIL GENERATION

During the optimisation process, the geometry of the airfoil is going to be modified and analysed several times. Airfoil has to be defined with as minimum parameters as possible to reduce the convergence time. Therefore, in this paper, B-spline shape functions are used to parameterize the geometry of the airfoil. The B-spline curves [5] are defined by control points, whose position when changed, yields a new curve as shown in the figures 2(a) and 2(b).

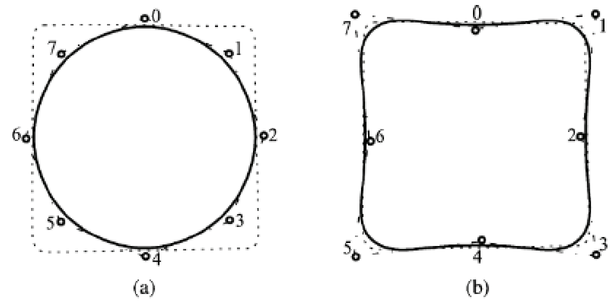

Figure 2: (a) represents curve before modification (b) modified curve due to movement of controls point (1),(3),(5),(7).

Two sets of control points define the suction and the pressure surface which then are combined to give the complete airfoil. The suction surface is defined by 6 control points and the pressure surface by 7. The order of the B-spline curve generated is 5[6] as shown in fig 3.

Out of the 13 control points, the two end control points of both the curves are fixed and are indicated by red in Figure 3. Out of 9 other points, point indicated by orange can move only in Y-direction and others can move in both directions. These control points form the design variables for the optimization algorithm. XFLR5 can be used to plot the airfoil and the shape can be controlled by defined number of control points. This is used to visualize the airfoil and give upper and lower bounds to maximum possible design space.

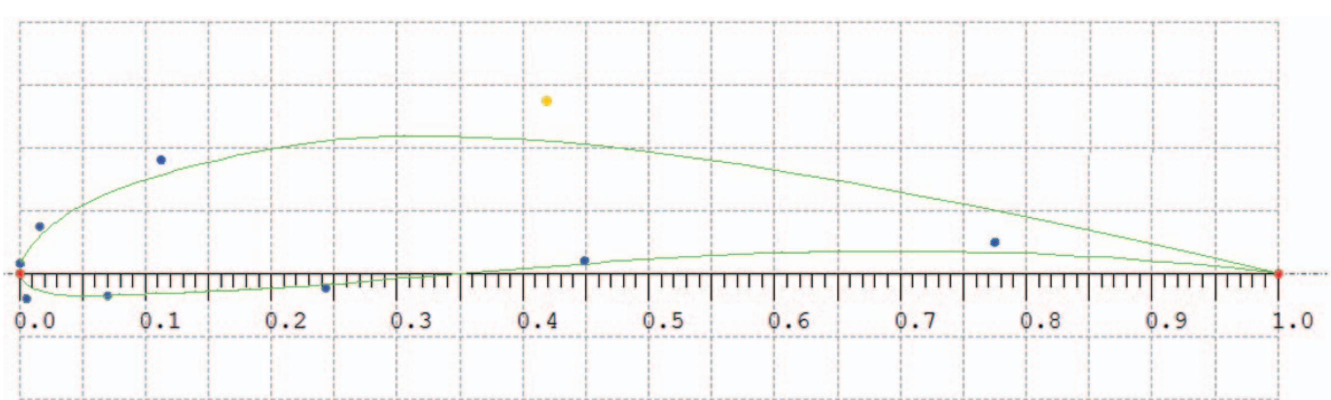

Figure 3: Location of Control points and their degrees of freedom

4. Optimization Methodology

The optimization algorithm used plays an important role and it is important to choose the right type of the solver for any given application. Obtaining an optimized airfoil is a non-smooth type of problem with many local minima. Pattern Search being a robust solver, it provably converges and is capable of handling various constraints [4]. Since it requires a user-supplied start point, selection of this initial vector plays a vital role in generating the most optimum airfoil.

Selection of airfoil for initial vector

The cruise velocity of the solar UAV was assumed to be 8-10 m/s and chord of the wing was estimated to be 350-400 mm in order to accommodate sufficient number of solar panels. This yielded a Reynolds Number of 2×10^5. To decide the initial vector, the airfoils [7] were evaluated at this Reynolds Number and chosen based on maximum values of C_L/C_D and $C_L{}^{1.5}/C_D$, where C_L and C_D are lift and drag coefficients respectively. The shortlisted airfoils are:

1. S1223
2. S1210
3. SG6043
4. FX 63-137

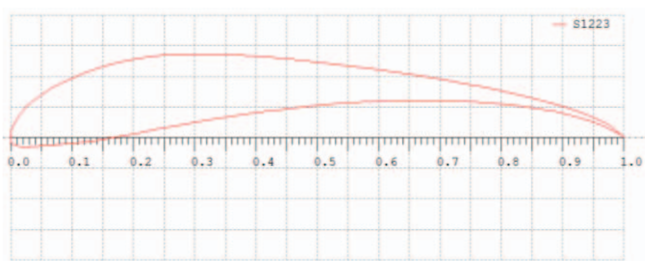

Figure 4: S1223

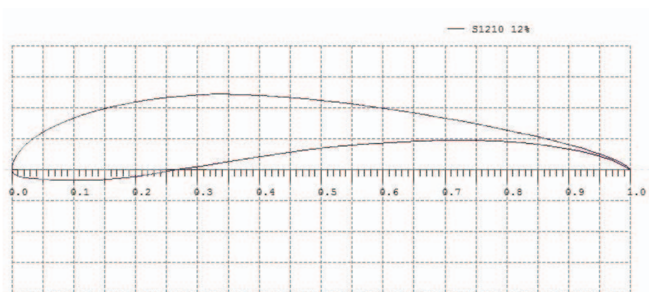

Figure 5: S1210

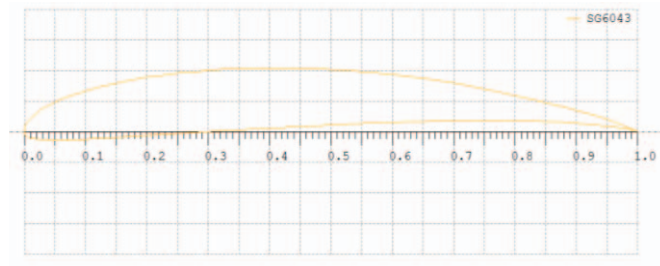

Figure 6: SG6043

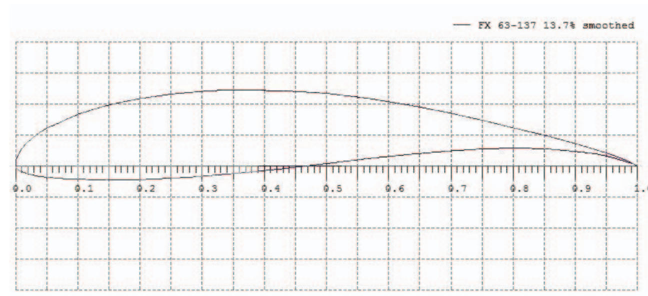

Figure 7: FX 63-137

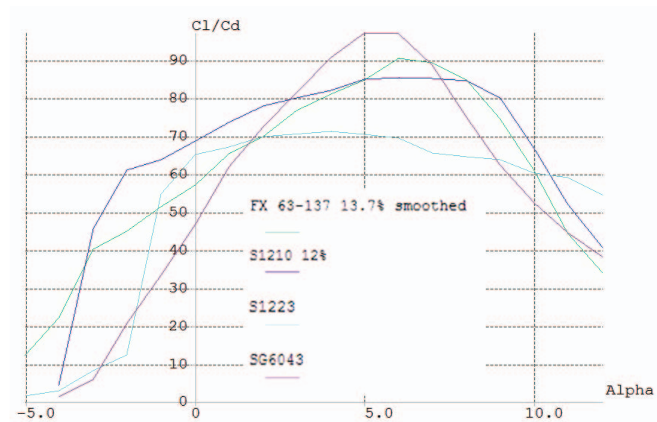

Figure 8: C_L/C_D vs. Angle of attack (Alpha) for shortlisted airfoils.

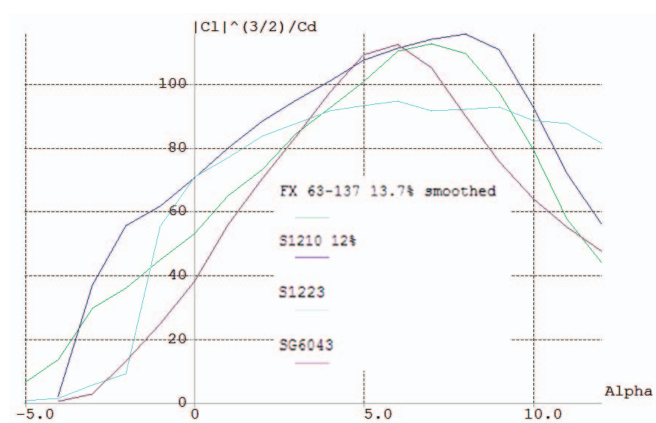

Figure 9: $C_L{}^{1.5}/C_D$ vs. Angle of attack (Alpha) for shortlisted airfoils.

The airfoils S1223 and S1210 had curvaceous suction surface which is impossible to modify the same to accommodate the panels. The suction surfaces of airfoils SG6043 and FX 63-137 could be modified but the drop in performance was significant in the operating angles of attack. Therefore, the airfoils were interpolated together in XFLR5. The suction surface towards the trailing edge was flattened by having no control points between 35% and 100% of the chord. This ensured that the generated B-spline curve had no flexibility [2] and hence can facilitate the mounting of the panels in that area. Having control point at 35% of the chord rendered the suction surface flat at least from 60% of the chord, depending on the position of the previous control. Also, from 35% to 60% of the chord, the curvature was minimal and within the flexibility limit of the panel and the substrate.

In addition, the airfoil is modified such that the width at 85% of the chord is set at 7mm to account for the thickness of the solar panel and its substrate. This modification ensured that optimization algorithm recognizes the high penalty given for violating this constraint and its implementation in the code is explained in later section. Finally, the control points of this airfoil forms the initial vector.

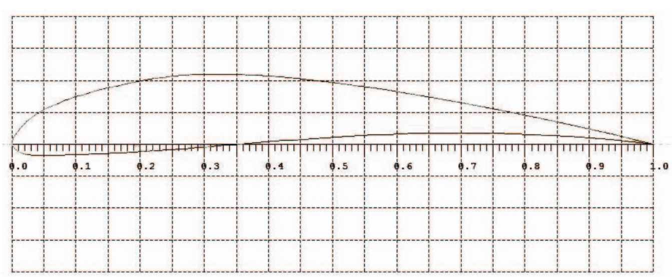

Figure 10: Initial airfoil which forms the basis for start-point for optimization algorithm.

Table 1: Control point coordinates of initial airfoil

Pressure surface		Suction surface	
X	Y	X	Y
1.0000	0.0000	1.0000	0.0000
0.7742	0.0251	0.3536	0.1460
0.4488	0.0100	0.0433	0.0526
0.2430	-0.0113	0.0248	0.0315
0.0697	-0.0178	0.0000	0.0100
0.0056	-0.0195	0.0000	0.0000
0.0000	0.0000		

XFOIL-MATLAB interface function

For XFOIL to evaluate the input airfoils, it is necessary to input a chain of commands, which enables it to access the file containing airfoil points, evaluate its performance and store the data in a user specified file. However, the optimization algorithm generally takes hundreds of iteration to converge at an optimal point. It would be imprudent to allow the user to monotonically input these commands. Therefore, automatizing this input process is essential to the entire process.

The XFOIL-MATLAB interface function achieves this while calling two other functions

1) *createdat.m* — Creates an input file (.dat) which would contain the point distribution of the intermediate airfoil, using B-spline method.

2) *scanoutput.m* — Scan the output file and access the C_L and C_D values as required by the objective function.

This interface function first calls createdat.m function, generating airfoil point distribution file. The width of the airfoil at 85% of the chord then accessed from this file and penalty is given if constraint is not satisfied.

The function then writes the sequence of commands into the input file to be supplied to XFOIL. The sequence of commands is provided in the Appendix B. All the generated airfoils are evaluated at a Reynolds Number of $2x10^5$ and the polars thus generated are stored in a file named outputfile.dat.

The scanoutput.m is then called to scan output file generated. The outputfile.dat is deleted automatically as XFOIL recognizes this file and appends the polar of the next airfoil to that of previous one.

The objective function then calculated, is the output of this function. Formation of objective function is explained in later section.

Computational time for XFOIL to evaluate an airfoil varies depending on the nose radius, thin sections towards trailing edge and the overall shape characteristics. Also, in the event of no-convergence of XFOIL, no value is written to the output file. In most of the cases, convergence cannot be achieved due to boundary layer separation and stall regions. Moreover, specific points can lead to numerical error and thus no convergence of XFOIL. Indeed when performing viscous analysis calculations, it is always a good idea to sequence runs so that the angle of attack does not change too drastically from one case to another [3]. Therefore, XFOIL is directed to evaluate for angle of attack ranging from -5 to 12. When no value output file is written, the scanoutput.m returns an error, thus disrupting the program. To ensure robustness of the program, test cases are implemented to check for the inconsistencies.

Objective function

The objective function is defined according to the requirements of the optimized airfoil which are as follows-

a) *Glide Ratio* ($^L/_D$)—since the solar UAV is essentially a glider, maximizing C_L/C_D of the airfoil at the operating angles of attacks is key to maximize the endurance [1].

b) *Power Factor* ($C_L{}^{1.5}/C_D$)—It can be inferred from the equation (1), maximizing $C_L{}^{1.5}/C_D$ at operating angles of attack makes it suitable for low-powered flight and thus increasing range[1].

$$P = \frac{C_D}{C_L{}^{1.5}}\sqrt{\frac{2W^3}{\rho S}} \tag{1}$$

c) *Manufacturing feasibility*—In order to accommodate for the solar panels along with its substrate, the width of the airfoil at 85 % of the chord should be at least 7mm.

The objective function is represented by the equation (2)

$$F \ = -\left\langle \sum_{A=-2}^{A=4} \frac{C_L{}^{1.5}}{C_D} + \sum_{A=-2}^{A=4} \frac{C_L}{C_D} \right\rangle + G \tag{2}$$

The values C_L/C_D and $C_L{}^{1.5}/C_D$ at operating range are obtained from the output file of the XFOIL-MATLAB wrapper. Since the optimization algorithm minimizes any function, the negative of the sum of all these values are considered for the objective function. If an airfoil does not meet the width criteria, high positive penalty G equal to 10000 is added to the objective function.

5. Results

Figure 9 shows both optimized airfoil and initial airfoil. The obtained optimized airfoil is compared with the initial airfoil. Table 2 represents the control point coordinates of both pressure surface and suction surface of the optimized airfoil starting from the trailing edge. The co-ordinates of the airfoil are enclosed in appendix A.

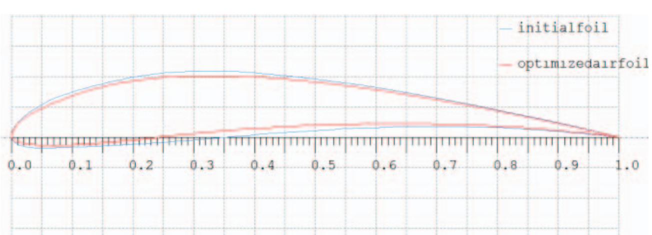

Figure 11: Optimized and initial airfoil

Table 2: Control point coordinates of optimized airfoil

Pressure surface		Suction surface	
X	Y	X	Y
1.0000	0.0000	1.0000	0.0000
0.6800	0.0288	0.3536	0.1460
0.3833	0.0227	0.0433	0.0526
0.2134	0.0035	0.0248	0.0315
0.0740	-0.0209	0.0000	0.0100
0.0000	-0.0150	0.0000	0.0000
0.0000	0.0000		

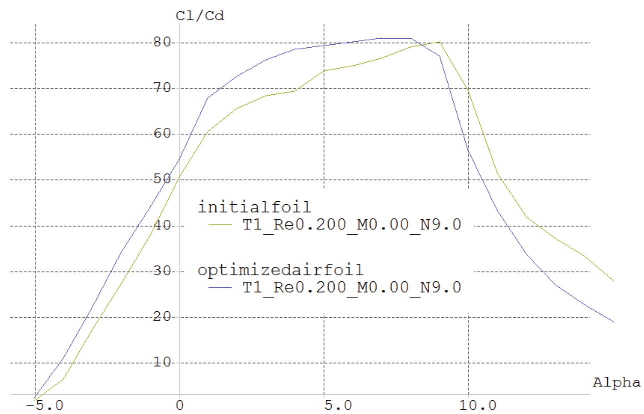

Figure 12: C_L/C_D vs. Angle of attack (Alpha) for initial and optimized airfoils.

Figure 12 shows the C_L/C_D comparison between the optimized airfoil and the initial airfoil. In the operating angles of attack the average increase in C_L/C_D of the optimized airfoil is 13.93%.

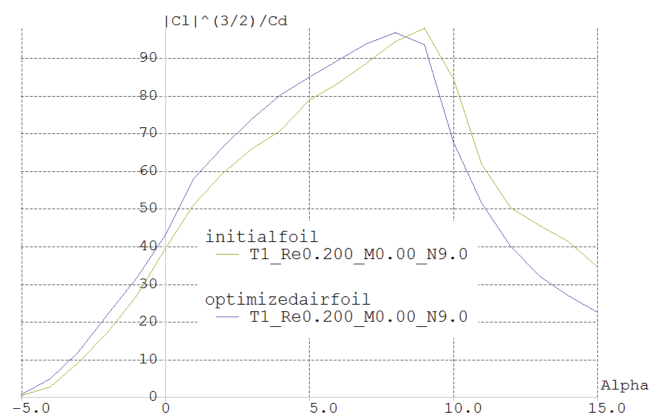

Figure 13: $C_L{}^{1.5}/C_D$ vs. Angle of attack (Alpha) for initial and optimized airfoils.

Figure 13 shows power factor comparison between the optimized airfoil and initial airfoil. In operating angles of attack the average increase in the power factor of the optimized airfoil is 15.21%.

6. Conclusion

The entire optimization process is quite flexible and a suitable airfoil can be obtained for various applications by giving appropriate constraints and penalties. Optimal airfoil obtained from this method will have superior aerodynamic characteristics than the manually modified airfoil as the optimization algorithm will carry out a comprehensive search of the design space.

However, the optimal airfoil given by pattern search algorithm is highly dependent on the initial vector. Better the initial vector, better is the output. However, since the problem is of non-smooth type, there are chances of optimization process converging at a local minima. Future work would to be conduct studies to avoid this situation.

Also, only C_L and C_D values for an airfoil were used to evaluate the aerodynamic performance. Further work can be carried out to include C_m (Moment co-efficient) and transition point. Minimizing C_m could decrease the size of the tail required for static stability and transition point could be incorporated in the code based on the placement of solar panels.

Finally, comparison of XFOIL results to that of another flow solver such as ANSYS FLUENT could serve as validation for the process presented. The process of airfoil optimization can be incorporated in the holistic design optimization of the entire UAV.

Appendicies

A. Final Equation of optimized Airfoil

Suction Surface equation

F (x) = p1*x^6 + p2*x^5 + p3*x^4 + p4*x^3 + p5*x^2 +

p6*x + p7

where x is normalized by mean 0.1914 and standard deviation 0.2534.

Coefficients (with 95% confidence bounds):

p1 = -0.001303 (-0.001788, -0.0008176)

p2 = 0.01048 (0.007218, 0.01373)

p3 = -0.0298 (-0.03641, -0.02319)

p4 = 0.03926 (0.03532, 0.04321)

p5 = -0.04694 (-0.05235, -0.04154)

p6 = 0.03446 (0.03165, 0.03726)

p7 = 0.09036 (0.08917, 0.09156)

Pressure Surface Equation

F (x) = p1*x^8 + p2*x^7 + p3*x^6 + p4*x^5 +

p5*x^4 + p6*x^3 + p7*x^2 + p8*x + p9

where x is normalized by mean 0.3323 and standard deviation 0.2729

Coefficients (with 95% confidence bounds):

p1 = 0.0005327 (0.000332, 0.0007334)

p2 = -0.003058 (-0.003986, -0.00213)

p3 = 0.004861 (0.003968, 0.005755)

p4 = 0.0005096 (-0.001885, 0.002904)

p5 = -0.004248 (-0.00693, -0.001566)

p6 = -0.003369 (-0.005726, -0.001012)

p7 = -0.005249 (-0.007138, -0.003361)

p8 = 0.02399 (0.02313, 0.02484)

p9 = 0.007991 (0.007698, 0.008285)

B. XFOIL Sequence of Commands

```
NORM                  // Normalise the airfoil
LOAD solarairfoil.dat // Load the airfoil
OPER                  // Toggle operational mode
VISC 2e+05            // Set to viscous mode and Re=2e5
ITER 200              // Set number of iteration to 200
PACC                  // Toggle auto accumulation to active polar
outputfile.dat        // The file where the points are to be stored

ASEQ -5 12 1          // Sequence of angle of attack to be evaluated for

QUIT                  // Quit XFOIL
```

ACKNOWLEDGEMENTS

The work presented in the paper involved analysis of a huge number of airfoils, and without a database the process could have been cumbersome. The authors like to thank UIUC for their open-source Airfoil database. The authors are grateful to Prof. C S Prasad for valuable guidance. The authors also thank Carl De Boor for B-spline curves which were of immense help in defining the airfoil geometry.

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BIOGRAPHY

__Anirudh Mukund Saraf__ is a senior year undergraduate student pursuing B.E Mechanical Engineering at Rashtreeya Vidyalaya College of Engineering (R.V.C.E), Bangalore, India. He is responsible for Aerodynamics in R.V.C.E Aero-design team which was the only Indian team to participate at AIAA DBF 2015. He was a summer intern at Hindustan Aeronautics Limited. His interests include UAV Aerodynamics and Astrodynamics. He is also a Student Member of AIAA.

__Chetan Vaidya__ is a senior year undergraduate student pursuing B.E Mechanical Engineering at Rashtreeya Vidyalaya College of Engineering (R.V.C.E), Bangalore, India. He is responsible for Propulsion subsystem in R.V.C.E Aero-design team which was the only Indian team to participate at AIAA DBF 2015. He was a summer intern at Hindustan Aeronautics Limited. His interests include Aerodynamics. He is also a Student Member of AIAA.

__Avinash Kini Mattar__ is a senior year undergraduate student pursuing B.E Mechanical Engineering at Rashtreeya Vidyalaya College of Engineering, Bangalore, India. He is responsible of Design and Stability in R.V.C.E Aero-design team which was the only Indian team to participate at AIAA DBF 2015. He was a summer intern at Hindustan Aeronautics Limited. His interests include System and control. He is also a Student Member of AIAA.

APPENDIX A

Summary of Format Requirements

Paper size
8.5 x 11 inch

Number of pages
6–20

Margins

Top and bottom:	0.75 inch
Left and right:	0.75 inch

Columns

Number of columns:	2
Space between:	0.25 inch

Font
Times Roman 10 pt regular, unless otherwise noted

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Line spacing:	Single
Space after paragraph:	10 pt
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Abstract
9 pt bold

Acronyms
Define acronyms on first usage

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Footnotes
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Centered in column
Equation numbers in parentheses, flush right
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