Research Article

Design and Analysis of Propeller for High-Altitude Search and Rescue Unmanned Aerial Vehicle

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The commercially available unmanned aerial vehicles are not good enough for search and rescue flight at high altitudes. This is because as the altitude increases, the density of air decreases which affects the thrust generation of the UAV. The objective of this research work is to design thrust optimized blade for an altitude range of 3,000–5,000 m with a density of air 0.7364 kg/m^3 , respectively, and perform thrust analysis. The property of aluminum alloy 1,060 being lightweight is chosen for designing and testing of blade. The blade element theory-based design and analysis code was developed, and user-friendly aerodynamic inputs were used to obtain the desired outputs. The geometry designed for an altitude range of 3,000–5,000 m faced the total stress of 6.0 MPa which was at 70% of the blade span. This stress is within the limit of yield strength of the aluminum alloy, 28 MPa. The modal analysis shows the first natural frequency occurs at around 12,000 RPM which is safe for operating the blade at 0–5,000 RPM. Experimental analysis of the blade gave a thrust of 0.92 N at 2,697 RPM at 1,400 m. The analytical solution for thrust with the same conditions was 1.7 N with 85.6% efficiency. The validation of experimental results has been done by the CFD analysis. The CFD analysis was performed in ANSYS CFX which gave a thrust value of 2.27 N for the same boundary conditions. Thus, the blade designed for high altitude SAR UAV is structurally safe to operate in 0–5,000 RPM range, and its use in search missions could save many lives in the Himalayas.

1. Introduction

Unmanned aerial vehicles (UAVs) have experienced rapid development in recent years. Impressive achievements have been made by the use of the UAV in civilian and military fields, for example, aerial photography, surveillance, remote sensing, agricultural monitoring, and fire control. There are many institutes which have been actively involved in exploring the more potential applications of UAV. These UAVs range from large (weight > 300 kg) [1, 2] to mini (takeoff weight < 300 kg, altitude 300 m) [3, 4] and even micro-UAVs (takeoff weight 5 kg, altitude 250 m) [5]. High altitude long endurance (HALE) UAV (17–25 km) [6] has been growing interest in recent years. The altitude and payload mass have a huge influence on the size and design of UAV [7]. Helios (wingspan 73 m) developed by NASA and UAS ascended to an altitude of over 29 km [6]. Unfortunately, Helios was destroyed during the flight test on June 26,

2003, because of turbulence and structural failure [8]. Similarly, Zephyr (wingspan 25 m, weight 75 kg) designed and built by British Company QinetiQ holds the official endurance world record of 14 days, 22 min, 8 sec without refueling [9].

The conventional airfoils such as the NACA airfoils were designed to operate at high Reynolds numbers [10]. Thus, for optimum aerodynamics characteristics, the low Reynolds number airfoil should be used for UAVs [11]. A few low Reynolds number ($Re < 300,000$) airfoil have been designed for the maximum lift to drag (C_l/C_d) ratio. [12, 13], such as A18 ($C_l/C_d = 79.6$), S6062 ($C_l/C_d = 73.1$), SD7032 ($C_l/C_d = 83.4$), and BW-3 ($C_l/C_d = 69.6$) [14]. For low speed and high lift to drag ratio ($C_l/C_d = 42.3$, at $Re 50,000$ and 3.25° AOA), S1223 airfoil is most suitable [15, 16].

Most UAVs have fixed pitch propellers [17, 18]. There are various theories which predict the efficiency of fixed-pitch propellers. Some are blade element theory, vortex theory [19], momentum theory [20, 21], flat plate theory

FIGURE 1: Percentage loss of thrust vs. altitude.

[22], and semiempirical methods [23]. Blade element theory is simple and efficient. It accounts for the Reynolds number effects in low advance ratios [24–26]. Thus, the blade element theory is widely used to model propeller blade aerodynamics.

Weerasinghe and Monasor [27] have carried out computational fluid dynamics (CFD) analysis and experimental wind tunnel tests on Syma X5SC quadrotor; even if simulation predictions were away from the experimental results at some flight conditions, CFD simulations were found good in describing complex flows of rotatory movements in overall [28]. Selig and Brandt found out that propeller performances decrease dramatically at lower rotational speeds with the effect of Reynolds number [29]. Past literature has shown that thrust and power coefficient determination methods mainly focused on wind tunnel and PIV measurements, CFD analysis, and analytical models [28].

The rescue operation of missing tourists in the Himalayas of Nepal is challenging. The authorities have to travel either by helicopter or on foot to the remote areas. The air being thin at higher altitudes makes it difficult to perform the rescue operation via UAVs. Liu et al. [30] found that with the increase in altitude, the UAV climb rate gradually decreases. It can be seen from Figure 1 that at 5,000 m altitude, thrust generation decreases by about 40%. This research work will help to improve propulsive efficiency for future SAR UAVs. The use of SAR will not only be limited in the field of search and rescue but also in high-altitude surveillance and mapping. The search and rescue UAV used by Mario and the team operated its flight from 300 masl to 2,600 masl. [31]. There are various UAVs which have been developed and tested with the purpose of surveillance and remote sensing for very high altitude [32–35]. Regarding the development of propeller for high altitude SAR UAVs, Korea Aerospace Research Institute have built the propeller with a diameter of 0.61 m to fly at 10 km ASL altitude with propeller efficiency

of 68% (at 3,120 RPM) [36]. The other 3-bladed propeller with 72% efficiency climbed at 22 km altitude with 0.5588 m diameter propeller generating 7 N thrust at 50 m/s free stream velocity [37].

In Nepal, UAVs have played a major role during an earthquake in 2015. But lack of rescue operations in the Himalayan has taken many innocent lives [38]. On April 30, 2018, the non-profitable organization National Innovation Centre tested its medical drone in remote village Rangi of Maygdi district, Nepal (altitude 2,300 masl) [39]. Although the flight was successfully tested, but the quadcopter performance was not satisfactory. There are various factors that affect the working of the propeller. The major ones are air density, size of the propeller blade, and pitch of the blade. We can see from Figure 1 that propeller thrust is directly proportional to the air density. In the atmosphere, air density decreases as the altitude increases. The relation between altitude and density is fairly exponential. This loss of thrust is due to the change in density of air which can be optimized by a differently designed propeller. Thus, the main objective here is to design and test the high-altitude fixed-pitch propeller of search and rescue unmanned aerial vehicles for maximum thrust.

The assumptions are as follows:

- (i) Fixed-pitch blade
- (ii) Chord (b) is given by equation (4)
- (iii) Blade span radius r is 0.15 m
- (iv) Two number of blades
- (v) Variations of the angle of attack do not affect the efficiency
- (vi) The chosen airfoil S1223 is an efficient design for higher altitude

FIGURE 2: Velocity vector diagram with reactions in the blade [43].

2. Methodology

2.1. Simple Blade Element Theory. Simple blade element theory is the most used propeller theory. In this theory, the blade is divided into different elements. Lift along with torque is calculated by each of these elements which is then summed to find total thrust and torque [40–42]. The total thrust for the propeller having B number of blades is given by equation (1). Similarly, the torque is given by equation (2), where B is the number of blades, ρ is the air density, V is the velocity, b is the chord, r is the radius of blade, and C_L is coefficient of lift. The efficiency is given by equation (3). Figure 2 [43] shows the velocity vector diagram with reactions in the blade.

$$F_t = \int_0^r \frac{1}{2} \rho V^2 b dr B C_L \frac{\cos(\gamma + \phi)}{\cos(\gamma) \sin^2(\phi)}, \quad (1)$$

$$Q = \int_0^r \frac{1}{2} \rho V^2 b dr r B C_L \frac{\sin(\gamma + \phi)}{\sin^2(\phi) \cos(\gamma)}, \quad (2)$$

$$\eta = \frac{F_t V}{2\pi n Q}. \quad (3)$$

It is assumed that the propeller tip which has the highest relative velocity does not exceed the speed of sound; thus, all the location does not exceed the speed of sound. It can be clearly seen from equation (3) that increasing the free stream velocity aids in increased efficiency.

2.2. Geometric Modelling. The design model is a linear and explicit type that the inputs for calculating thrust and other forces are solved by known input parameters such as density and earth's altitude. It is time-dependent and the approach is deterministic. Thrust calculation was based on equation (1); other assumed parameters are the density of air at 4,000 m

TABLE 1: Aluminum alloy properties.

Descriptions	Standard value (at 25°C)
Density	2700 kg/m ³
Modulus of elasticity	69 MPa
Tensile strength	69 MPa
Yield strength	28 MPa
Poisson's ratio	0.33

is 0.8194 kg/m³, the number of blades is 2, C_L and C_D for AOA 4° is 1.35 and 0.05, Re is 33,000, the radius of the blade is 0.15 m, and the chord is given by equation (4) [44]. The propeller will be used with 0-4000 RPM limit, whereas for the factor of safety, certain analysis has been performed till 5,000 RPM.

$$b = (0.08424 - 0.08579r + 4.7176r^2 - 9.6225r^3 + 8.5004r^4 - 2.7959r^5) D. \quad (4)$$

In Table 1, aluminum alloy properties give the aluminum alloy 1,060 physical properties. The compositions include Si = 0.25%, Fe = 0.25%, and Al = 99.5%. This value is used for calculations and analysis here. Figure 3 shows the maximum thrust received by the blade is 3.35 N at 4,000 RPM. The figure also shows thrust generation for 500-3,500 RPM. The increasing trend suggests that the thrust generation will increase rapidly if the rotational velocity is increased. But vibration analysis should be carried out for increasing the RPM.

The three different blades that have been designed for the same thrust output (3.35 N) are shown in Figure 4. If the

FIGURE 3: Generation of thrust for the blade designed to operate at 4,000 m altitude.

FIGURE 4: The geometry of blade for 3 different altitudes for the same thrust generation 3.35 N.

blade with the same thrust generation of 3.35 N is used at sea level altitude, then the required radius reduces to 134 mm. Similarly, the blade is used at an altitude of 8,000 m for the same thrust output that the required radius is increased to 167 mm. The blade used for altitude 4,000 m was further analyzed at different free stream velocity, i.e., 10 m/s, 50 m/s, 100 m/s (shown in Figure 5). With a higher velocity of air, a higher twist angle was required as shown in Figure 6. For the analysis purpose, the blade designed for 4,000 m altitude and 10 m/s velocity is chosen here. The designed blade has 7.1 mm thick root and 1.5 mm thin tip.

FIGURE 5: Cross-section of the blade for three different velocities.

3. Structural Design and Analysis

3.1. Shear Force and Bending Moment. The shear force and bending moment diagram of the blade can be seen in Figures 7 and 8. The bending moment is based on resultant thrust loading. Since the thrust force acts upwards, the bending moment acts downward or anticlockwise. Furthermore, as the radius of the blade increases, the shear force and bending moment increases as well. All this analysis is limited to 5,000 RPM, because this is the maximum speed the blade may face. The geometry of the blade is designed for 4,000 RPM only. So, for the factor of safety, structural analysis was performed till 5,000 RPM. Increasing the speed higher than 5,000 RPM will cause the blade root to face more stress and may fail.

3.2. Stress Concentration. The load produced by lift force causes the blade to withstand bending stress and the

FIGURE 6: Variation of twist angle for three different velocities.

FIGURE 7: Bending moment.

FIGURE 8: Shear force.

rotational speed causes centrifugal stress. The stress concentration is calculated using equation (5).

$$\sigma_b = \frac{My}{I}, \sigma_c = \frac{mv^2}{rA}, \quad (5)$$

where σ_b is the stress produced due to bending moment, σ_c is the stress produced due to centrifugal force, M is the calcu-

lated bending moment, y is the vertical distance, I is the moment of inertia, m is mass of blade, and A is the area of the airfoil at a particular section.

Figure 9 shows total stress distribution and the combination of centrifugal and bending stress along the span of the blade. The maximum stress (6.5 MPa) faced by the blade is at 70% of the blade span towards the root and 2.7 MPa at the root. This stress compared to aluminum yield strength

FIGURE 9: Combined stress developed in the blade.

FIGURE 10: Total stress distribution.

28 MPa is in the limit; thus, the blade is safe to operate with a rotational velocity of 0-5,000 RPM. In Figure 10, we can see the results of total stress distribution which is obtained from ANSYS 18. It can be seen that with the same boundary conditions and at 4,000 RPM, the maximum stress is 9.35 MPa. Thus, the blade will operate with out failure within the rotational speed of 0-4,000 RPM.

3.3. Modal Analysis. Figure 11 shows the Campbell diagram for the blade with propeller rotation speed in x -axis and system frequency in y -axis. It can be seen that the first natural frequency of the blade occurs at 200 Hz ($200 \text{ Hz} \times 60 = 12,000 \text{ RPM}$), operating the blade at 12,000 RPM will excite the critical frequency at 4,500 RPM which may lead to failure. But the blade operating range is 0-4,000 RPM; thus, it is safe from resonance and other modes of vibrations.

4. CFD Analysis

4.1. Computational Model. The computational domain is divided into 2 parts (Figure 12). The stationary domain takes

FIGURE 11: Campbell diagram.

10 times the diameter of the propeller in upstream and downstream. The span-wise diameter is 10 times. Inlet, outlet, and propeller outer region are stationary. The rotating domain with cylindrical shape has diameter 400 mm and height 400 mm. Figure 13 shows individual mesh for stationary and rotating domains along with the propeller blade. Figure 14 shows the mesh independence test. Three different mesh structure was used to guarantee the results' independency at the propeller rotation speed of 2,679 rpm. The number of

FIGURE 12: Computational domain and boundary conditions.

FIGURE 13: Mesh for (a) rotating domain, (b) stationary domain, and (c) propeller blade.

course mesh is 0.39 million; the used mesh (fine mesh) is made by 0.42 million cells. The maximum discrepancy between the fine mesh and the course mesh is only 0.26% for the generated thrust. Thus, the results are not affected by the used mesh. Hence, the fine mesh is used in the CFD simulation of the designed propeller.

The mesh quality metrics are to assess the suitability of a computational domain for simulations. There are various parameters that define the mesh quality. Such as most of the element's aspect ratio is 7-9. Furthermore, Figure 15 shows the element quality and Figure 16 shows the orthogonal quality. It can be noticed from Figures 15 and 16 that not

FIGURE 14: Mesh independence.

FIGURE 15: Element quality.

FIGURE 16: Orthogonal quality.

TABLE 2: Boundary conditions.

Inlet boundary conditions	
Inlet type	Velocity inlet
Velocity	1 m/s
Wall boundary conditions	
Wall motion	Stationary wall
Shear condition	No slip
Outlet boundary conditions	
Outlet type	Pressure outlet
Gauge pressure	0 Pa
Solution method	
Scheme	Second-order upwind
Properties of flowing fluid	
Fluid	Air at 20 °C
Density	1.07 kg/m ³

FIGURE 17: 3D printed and aluminum casted blade together.

all the 0.4 million elements are shown. This is because the bad quality elements are very small in number, and it is hard or near impossible to spot in a full-scale figure.

4.2. Computational Method. The flow field of the propeller is stationary under the rotating coordinate system. The ANSYS CFX turbo mode is used to solve the problem. Reynolds-Averaged Navier-Stokes equations are regarded as the governing equations. The finite volume method with the pressure-based solver is used to discretize the governing equations. Second-order upwind (high resolution) is used for the advection scheme. Pérez et al. carried out the CFD of the quadrotor's propeller and found out that k- ω and Spalart Allmaras turbulence models both overestimated thrust and torque compared with experimental results taken from flight tests [45]. In order to simulate the turbulence, the standard k- ϵ model [46] which requires flow to be fully turbulent is used [47]. The convergence is also guaranteed by monitoring the residual value which drops below 1.0×10^{-3} .

4.3. Boundary Conditions. All the boundary conditions are applied based on the experiment carried out at 1,400 m.

FIGURE 18: Thrust test bed.

TABLE 3: Thrust rating obtained experimentally.

Sn	RPM	Thrust (kg)	Thrust (N)
1	990	0.004	0.0393
2	1256	0.023	0.226
3	2679	0.095	0.932

TABLE 4: Comparison of thrust generation.

Altitude	Analytical	Numerical	Experimental (off-design)	Remarks
1400 m	1.70 N	2.27 N	0.92 N	At 2679 RPM

The flowing fluid is considered as air at 20°C and the flow is steady. The boundary conditions are shown in Table 2 which are the assumptions based on the past authors' work [15, 48–50].

5. Manufacturing and Testing

The designed blade was 3D printed first, and sand casting was performed. The final results can be seen in Figure 17. The aluminum alloy 1,060 was used for casting. A static balance check was performed before the final thrust test. The thrust testbed can be seen in Figure 18. The test rig was chosen as length 1 m and height 1 m. The test condition includes the free stream velocity of air as negligible as the testbed was fixed. The thrust test results are shown in Table 3. The blade developed the thrust of 0.932 N at 2,679 RPM. Due to the testbed limitations, higher RPM could not be tested. Although the blade was designed for higher altitude, the test was carried out at 1,400 m. The propeller was made up of aluminum, and to test it, we needed a testbed enclosed inside a box with one side open to atmosphere. Carrying the testbed to a higher altitude was empirically challenging from both financial and technical perspectives. Thus, the experiment was carried out at 1,400 m altitude.

FIGURE 19: Pressure side of the blade.

FIGURE 20: Suction side of the blade.

6. Results and Discussions

The results obtained from analytical values and experimental and numerical values have been compared. The comparison of all values can be seen in Table 4. The experimental value gave 0.92 N thrust at 2,679 RPM. The corresponding value from analytical calculations were 1.7 N. The CFD analysis gave the corresponding value of 2.27 N at 2,679 RPM. The experimental results and analytical value gave 45% test results. This could be due to various factors involved in the experiment. Such as for safety purposes, an experiment was conducted inside a closed room so the free stream air velocity was ignored; aerodynamics profile

of the fabricated propeller may not be accurately the same to the designed propeller.

The pressure contours as seen in Figures 19 and 20 show the pressure distribution profile. The blade faced the highest pressure of 651 Pa at the pressure side and the lowest pressure of -700 Pa at the suction side.

7. Conclusion

The blade was designed for an altitude range of 3,000-5,000 m which is suitable for search and rescue operations in Nepal. Although the blade could not be tested at high altitude, but the test results performed at the IOE laboratory and

CFD analysis show that it can be used for SAR missions in Nepal. Here are the conclusions that can be drawn from this research work.

- (i) The CFD thrust analysis gave thrust generation of 2.27 N for an altitude of 1,400 m with a rotational velocity of 2,679 RPM. Experimental thrust 0.92 N was less accurately predicted by CFD. Past literature has shown the error between CFD, and the experiment varied from 14 to 24% [49, 51]. However, here, numerical analysis results differ largely from experimental results. From Figure 14, we can see that with more element size mesh, we get more accurate results. Thus, further investigations are suggested in order to reduce the differences in the results
- (ii) The total stress faced by the blade is 6 MPa which is around 70% span of the blade which is safe for the blade compared to aluminum yield strength of 28 MPa
- (iii) The thrust rating test showed the thrust generation of 0.92 N at 2,679 RPM. The analytical value based on test conditions for 2,679 RPM would be 1.7 N. This gives 45% of the test results

Abbreviations

AOA:	Angle of attack
b :	Chord length
FEA:	Finite element analysis
IOE:	Institute of Engineering
masl:	Meter above sea level
PIV:	Particle image velocimetry
n :	Revolution per sec
Re:	Reynolds number
SAR:	Search and rescue
UAS:	Aeronautical environment corporation
σ_b :	Stress produced due to bending moment
σ_c :	Stress produced due to centrifugal force
I :	Moment of inertia
η :	Efficiency
β :	Blade/helix angle
ρ :	Density of air
r :	Radius of blade
α :	Angle of attack
$\varnothing$:	Flow angle
γ :	Angle between reaction force (lift and drag components) and lift
V_{rel} :	Relative velocity
V_o :	Free stream velocity
V_{rot} :	Rotational velocity.

Data Availability

The data used to support the observations of this study are available from the corresponding author upon request.

Disclosure

The funding institute had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Conflicts of Interest

The authors declare that there is no conflict of interest with regard to the publication of this paper.

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References

- [1] P. L. Coronado, F. Stetina, and D. Jacob, "New technologies to support NASA's Mission to Planet Earth satellite remote sensing product validation: use of an unmanned autopiloted vehicle (UAV) as a platform to conduct remote sensing," *Robotic and Semi-Robotic Ground Vehicle Technology*, vol. 3366, pp. 38–49, 1998.
- [2] S. R. Herwitz, L. F. Johnson, J. C. Arvesen, R. G. Higgins, J. G. Leung, and S. E. Dunagan, "Precision agriculture as a commercial application for solar powered unmaned aerial vehicles," in *AIAA's 1st Technical Conference and workshop on Unamnned Aerospace Vehicles*, p. 7, Portsmouth, Virginia, 2002.
- [3] L. F. Johnson, S. Herwitz, S. Dunagan, B. Lobitz, D. Sullivan, and R. Slye, "Collection of ultra high spatial and spectral resolution image data over California vineyards with a small UAV," *Proceedings of the 30th International Symposium on Remote Sensing of Environment (ISRSE)*, pp. 3–5, 2003, <http://www.uav-applications.org/gallery/img/5.pdf>.
- [4] H. Eisenbeiss, "A mini unmanned aerial vehicle (UAV): system overview and image acquisition," *International Archives of Photogrammetry. Remote Sensing and Spatial Information Sciences*, vol. 36, no. 5/W1, p. 7, 2004.
- [5] S. Nebiker, A. Annen, M. Scherrer, and D. Oesch, "A light-weight multispectral sensor for micro UAV-opportunities for very high resolution airborne remote sensing," *The international archives of the photogrammetry, remote sensing and spatial information sciences*, vol. 37, pp. 1193–1199, 2008.
- [6] G. Romeo, G. Frulla, E. Cestino, and G. Corsino, "HELIPLAT: design, aerodynamic, structural analysis of long-endurance solar-powered stratospheric platform," *Journal of Aircraft*, vol. 41, no. 6, pp. 1505–1520, 2004.
- [7] S. Jashnani, T. R. Nada, M. Ishfaq, A. Khamker, and P. Shaholia, "Sizing and preliminary hardware testing of solar powered UAV," *The Egyptian Journal of Remote Sensing and Space Science*, vol. 16, no. 2, pp. 189–198, 2013.
- [8] T. E. Noll, J. M. Brown, M. E. Perez-davis, S. D. Ishmael, G. C. Tiffany, and M. Gaier, *Investigation of the Helios Prototype Aircraft Mishap*, 2004, https://www.nasa.gov/pdf/64317main_helios.pdf.
- [9] X. Zhu, Z. Guo, and Z. Hou, "Solar-powered airplanes: a historical perspective and future challenges," *Progress in Aerospace Science*, vol. 71, pp. 36–53, 2014.

- [10] J. B. McDevitt and A. F. Okuno, *Static and Dynamic Pressure Measurements on a Naca 0012 Airfoil in the Ames High Reynolds Number Facility*, 1985.
- [11] E. Llorente, A. Gorostidi, M. Jacobs, W. A. Timmer, X. Munduate, and O. Pires, "Wind tunnel tests of wind turbine airfoils at high Reynolds numbers," *Journal of Physics Conference Series*, vol. 524, no. 1, p. 10, 2014.
- [12] P. Giguère and M. S. Selig, "New airfoils for small horizontal axis wind turbines," *The Journal of Solar Energy Engineering*, vol. 120, no. 2, pp. 108–114, 1998.
- [13] R. K. Singh, M. R. Ahmed, M. A. Zullah, and Y. H. Lee, "Design of a low Reynolds number airfoil for small horizontal axis wind turbines," *Renewable energy*, vol. 42, pp. 66–76, 2012.
- [14] P. Shin and K. Kim, "Aerodynamic performance prediction of SG6043 airfoil for a horizontal-axis small wind turbine," *Journal of Physics: Conference Series*, vol. 1452, no. 1, p. 11, 2020.
- [15] S. Sharma, "An aerodynamic comparative analysis of airfoils for low-speed aircrafts," *International Journal of Engineering Research*, vol. V5, no. 11, pp. 525–529, 2016.
- [16] S. A. Oller, L. G. Nallim, and S. Oller, "Usability of the selig S1223 profile airfoil as a high lift hydrofoil for hydrokinetic application," *Journal of Applied Fluid Mechanics*, vol. 9, no. 2, pp. 537–542, 2016.
- [17] R. R. Glasscock, *Design, Modelling and Measurement of Hybrid Powerplant for Unmanned Aerial Vehicles (UAVs)*, Queensland University of Technology, 2012.
- [18] W. A. Mair and D. L. Birdsall, *Aircraft Performance*, Cambridge University Press, 2009.
- [19] B. A. Moffitt, T. H. Bradley, D. E. Parekh, D. Mavris, and E. Hartford, "Validation of vortex propeller theory for UAV design with uncertainty analysis," in *46th AIAA Aerospace Sciences Meeting and Exhibit*, pp. 1–19, 2008.
- [20] M. K. Rwigema, "Propeller blade element momentum theory with vortex wake deflection," *27th International congress of the aeronautical sciences*, vol. 1, pp. 727–735, 2010.
- [21] W. F. Phillips, "Propeller momentum theory with slipstream rotation," *Journal of Aircraft*, vol. 39, no. 1, pp. 184–187, 2002.
- [22] L. A. Viterna, *Fixed Pitch Rotor Performance Of Large Horizontal Axis Wind Turbines.*, N83 19233, 1982.
- [23] B. Montgomerie, *Methods for Root Effects, Tip Effects and Extending the Angle of Attack Range to +180, with application to Aerodynamics for Blades on Wind Turbines and Propellers.pdf*, 2004.
- [24] J. Morgado, M. A. R. Silvestre, and J. C. Páscoa, "Validation of new formulations for propeller analysis," *Journal of Propulsion and Power*, vol. 31, no. 1, pp. 467–477, 2015.
- [25] M. Ol, C. Zeune, and M. Logan, "Analytical-experimental comparison for small electric unmanned air vehicle propellers," in *Collection of Technical Papers-AIAA Applied Aerodynamics Conference*, p. 17, Honolulu, Hawaii, 2008.
- [26] M. McCrink and J. W. Gregory, "Blade element momentum modeling of low-re small UAS electric propulsion systems," in *Applied Aerodynamics Conference AIAA*, pp. 1–23, Dallas, Texas, 2015.
- [27] R. Weerasinghe and M. Monasor, *Simulation and Experimental Analysis of Hovering and Flight of a Quadrotor*, 2017.
- [28] Y. Eraslan, E. Özen, and T. Oktay, "A literature review on determination of quadrotor unmanned aerial vehicles propeller thrust and power coefficients," *Ejona X-International Conference on Mathematics-Engineering-Natural & Medical Sciences*, pp. 1–12, 2020.
- [29] J. Brandt and M. Selig, "Propeller performance data at low reynolds numbers," in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, pp. 1–18, 2011.
- [30] R. L. Liu, Z. J. Zhang, Y. F. Jiao, C. H. Yang, and W. J. Zhang, "Study on flight performance of propeller-driven UAV," *International Journal of Aerospace Engineering*, vol. 2019, 11 pages, 2019.
- [31] M. Pólka, S. Ptak, and Ł. Kuziora, "The use of UAV's for search and rescue operations," *Procedia Engineering*, vol. 192, pp. 748–752, 2017.
- [32] G. Frulla and E. Cestino, "Design, manufacturing and testing of a HALE-UAV structural demonstrator," *Composite Structures*, vol. 83, no. 2, pp. 143–153, 2008.
- [33] S. Jung, Y. Jo, and Y. J. Kim, "Aerial surveillance with low-altitude long-endurance tethered multirotor UAVs using photovoltaic power management system," *Energies*, vol. 12, no. 7, 2019.
- [34] J. Biesemans, J. Everaerts, and N. Lewycky, "Pegasus: remote sensing from a HALE-UAV," *ASPRS annual convention*, vol. 1, pp. 53–56, 2005.
- [35] J. Everaerts, "The use of unmanned aerial vehicles (UAVs) for remote sensing and mapping," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 37, pp. 1187–1191, 2008.
- [36] D. Park, T. Cho, C. Kim, Y. Kim, and Y. Lee, "Performance evaluation of propeller for high altitude by using experiment and computational analysis," *Journal of the Korean Society for Aeronautical & Space Sciences*, vol. 43, no. 12, pp. 1035–1047, 2015.
- [37] K. You, X. Zhao, S. Z. Zhao, and M. Faisal, "Design and optimization of a high-altitude long endurance UAV propeller," in *IOP Conference Series: Materials Science and Engineering*, Kuala Lumpur, Malaysia, 2020.
- [38] P. Gyawali and C. Dahal, "Using a GPS enabled body area network (BAN) based health tracker, that uses GSM, for mountaineers in Nepal," *International Astronautical Congress*, p. 6, 2018.
- [39] G. Sharma, *Nepal's Medical Drones bring Healthcare to the Himalayas*, Reuters, 2018.
- [40] A. Dumitrache, M. V. Pricop, M. I. Niculescu, M. G. Cojocaru, and T. Ionescu, "Design and analysis methods for UAV rotor blades," *Scientific Research & Education in the Air Force-AFASES*, vol. 19, no. 1, pp. 115–126, 2017.
- [41] A. H. Yates, "Elements of propeller and helicopter aerodynamics. D. O. Dommasch. 178 pp. pitman. 35s. Net," *Journal of the Roy Aeronautical Society*, vol. 57, no. 511, pp. 473–473, 1953.
- [42] A. H. Yates, "Aircraft propeller design," *Journal of the Aeronautical Sciences*, vol. 8, 1941.
- [43] R. Dasilveira, *Optimum Propeller Designs for Electric UAVs*, Auburn University, 2002.
- [44] X. Liu and W. He, "Performance calculation and design of stratospheric propeller," *IEEE Access*, vol. 5, pp. 14358–14368, 2017.
- [45] A. M. G. Pérez, O. D. López, and J. A. Escobar, "Computational study of the wake of a quadcopter propeller in hover," in *23rd AIAA Computational Fluid Dynamics Conference*, pp. 1–9, Denver, Colorado, 2017.

- [46] B. E. Launder and D. B. Spalding, "The numerical computation of turbulent flows," *Computer Methods in Applied Mechanics and Engineering*, vol. 3, no. 2, pp. 269–289, 1974.
- [47] M. Abdulkadir, V. Hernandez-Perez, S. Lo, I. S. Lowndes, and B. J. Azzopardi, "Comparison of experimental and computational fluid dynamics (CFD) studies of slug flow in a vertical 90° bend," *The Journal of Computational Multiphase Flows*, vol. 5, no. 4, pp. 265–281, 2013.
- [48] J. Singh, J. Singh, A. Singh, A. Rana, and A. Dahiya, "Study of NACA 4412 and Selig 1223 airfoils through computational fluid dynamics," *SSRG International Journal of Mechanical Engineering (SSRG-IJME)-volume*, vol. 2, no. 6, pp. 17–21, 2015.
- [49] T. Oktay and Y. Eraslan, "Computational fluid dynamics (Cfd) investigation of a quadrotor UAV propeller," in *International Conference on Energy, Environment and Storage of Energy (ICEESEN 2020)*, pp. 1–5, Talas, Turkey, 2020.
- [50] C. Kong, H. Park, K. Lee, and W. Choi, "A study on structural design and analysis of composite propeller blade of turboprop for high efficiency and light weight," in *ECCM 2012- Composites at Venice, Proceedings of the 15th European Conference on Composite Materials*, pp. 24–28, Venezia, Italy, 2012.
- [51] S. Kandwal and S. Singh, "Computational fluid dynamics study of fluid flow and aerodynamic forces on an airfoil," *International Journal of Engineering Research & Technology*, vol. 1, no. 7, pp. 1–8, 2012.