AIAA SciTech Forum
6-10 January 2020, Orlando, FL
AIAA Scitech 2020 Forum

10.2514/6.2020-2018

Design a Fixed-Wing Unmanned Aerial Vehicle with Dynamic Soaring Capability for Titan Exploration

Victoria Pellerito[1,2], Micaela Olivas[3], Mostafa Hassanalian[4]*

Planetary exploration can reach new heights through the use of space drones; particularly when comparing the mapping capabilities to those of a rover or satellites and orbiters. A drone is capable of reaching greater distances than a rover while maintaining a higher resolution than orbiters. In studying Titan, Saturn's largest moon, the employment of space drones is worth investigation due to its Earth-like atmosphere. A fixed-wing drone with a tapered wing shape, an aspect ratio of 4, a wingspan of 5.17 m, and a total weight of 270 N is designed for Titan exploration. A possible method for exploring Titan is utilizing a liquid methane propelled drone that is designed to perform low-altitude dynamic soaring with the capability to refuel from the moon's methane oceans. The opportunity to utilize the methane from Titan's oceans will diminish the drawback of large energy consumption and allow for a lengthier exploration of the moon.

I. Introduction

Within the past decade, researchers have begun to implement drones for the enhancement of space exploration[1-5]. Satellites, orbiters, rovers, and astronauts have all been previously used to investigate the planets, but recent technological advancements have suggested that drones may present numerous advantages for space exploration[6]. The increased exploration abilities and the increased quality of both footage and data collection provided by drones demands the pursuit of their implementation[7-11]. Planetary exploration can reach new heights through the use of drones, as they are capable of reaching greater distances than a rover while maintaining a higher resolution than orbiters[7]. In studying many of the other solar bodies, like Titan, Saturn's largest moon, the employment of space drones is worth investigation due to its Earth-like atmosphere. Titan was discovered to have an atmosphere in 1944 and was first explored by Pioneer 11 as it passed through Saturn's system in 1979, which confirmed the moon's temperature and mass. The thick, opaque atmosphere of Titan prevented Voyager 1 and 2 from capturing any visual features of the moon's surface in their 1980 and 1981 missions. However, they were able to discover the high concentration of nitrogen within the atmosphere, in addition to finding traces of acetylene, ethane, and propane[12]. In 2004, the Cassini spacecraft paired with the European Space Agency's Huygens probe was the first human-made orbiting object of Saturn and the first to see through the hazy atmosphere. In 2005, Huygens landed on Titan's surface, but only transmitted data for a few hours before the batteries died[13].

Although highly rewarding and conceptually ideal, the employment of drones for space missions such as Titan has many challenges to be faced. The harsh environments including low temperatures, high pressures, and unpredictable weather conditions require elaborate materials and manufacturing[3]. However, the biggest drawback for space drone applications is the high energy consumption necessary for continuous flight. A solar-powered drone might seem like a worthy choice; however, the distance from the sun, and the thick, hazy atmosphere of Titan limits the potential for solar power applications[14,15]. Titan does not provide enough power to lift even the wings of the later proposed drones in section III. Calculations were

[1]Undergraduate REU Student, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA.
[2]Undergraduate Student, Department of Mechanical Engineering, Lawrence Technological University, Southfield, MI 48075, USA.
[3]Undergraduate Student, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA.
[4]Assistant Professor, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA.

performed using Table 4 (seen in part III), the solar flux hitting Titan's surface (0.17 W/m^2), the gravity on Titan (1.352 m/s^2), and the 50W/lb of aircraft rule for flight[16]. The calculations revealed that Titan can only provide 1.1339 W to the planform area of the drone, while approximately 22 kW is required to lift merely the wings of the drone. A solar-powered exploration drone is highly impractical for flight on Titan and pales in comparison to the capabilities of a methane-powered drone. Although the use of drones introduces a series of challenging design constraints for long-term space applications, they have remarkable capabilities in planetary exploration.

Scientists have been interested in the application of various modes of flight to search for complex organic molecules on the surface of Titan[1]. The moon has a substantial atmosphere, much like that of the Earth, and is the only moon that contains liquid lakes, rivers, and seas. Scientists believe that it is possible that life can be found among the sub-surface water with prebiotic chemical processes. This belief has driven researchers to create a vehicle with the capability to travel to Titan, and explore the moon's life, geography, and atmosphere, among other countless research topics[17]. Previous NASA mission concepts included balloon applications that evolved into the discussion and design of drones for further exploration. A possible method for exploring Titan is utilizing a gas propulsion drone that is designed to soar from lower to higher altitudes with capabilities to perform methane ocean landings. This will allow for the drone to land on Titan's methane ocean and float while replenishing its fuel supply. The opportunity to utilize the methane from Titan's oceans will diminish the drawback of large energy consumption and allow for a lengthier exploration of the moon.

With Titan's atmosphere being similar to Earth's atmosphere, which is composed of predominantly nitrogen, the moon can be considered as a prime target for space drone flight. The composition of Titan's atmosphere allows for an easier drone flight than on the Earth; this makes drones an ideal mode for exploration on the moon. The probability of atmospheric flight on Titan has been investigated for a potential post-Cassini mission. A space drone that is capable of exploring both the dense atmosphere as well as the surface of Titan is ideal, which shines light on the proposed design of UAV capable of low-altitude flights and methane ocean landings. The matter is considered to be both timely and necessary as it is evident that the moon is full of opportunities for scientific research[18].

This paper proposes an unmanned aerial vehicle with dynamic soaring capabilities for Titan exploration. The vehicle will have the ability to provide sampling, analysis, and imaging of Titan's surface and atmosphere; it will be capable of landing on liquid methane lakes, which will be used as a fuel source, and it will utilize dynamic soaring at optimal elevations to conserve energy. The aerial vehicle will also be designed to withstand the low temperatures and high densities found within the Titan moon (see Table 1).

Table 1. Comparison of Titan and Earth[1].

Parameter	Titan	Earth
Temperature [K]	93	288
Density [kg/m^3]	5.25	1.2
Pressure [bar]	1.5	1
Viscosity [m^2/s]	6.3x10^{-6}	1.8x10^{-5}
Gravity [m/s^2]	1.35	9.81

II. Titan Exploration by Drones

The idea of exploring Titan via drones has been developing over the past decade. The early theory began in 2008 when NASA and the ESA developed the Montgolfiere style balloon concept. A pathfinder would explore the surface of Titan while the balloon would act as a flagship. The idea later evolved until the use of a drone was presented. NASA John Hopkins University Applied Physics Laboratory proposed a conceptual Titian exploration mission via space drones in February 2017[18]. The drone termed the Dragonfly, utilized an eight-bladed rotor design. Vertical takeoff and landing capabilities would allow the Dragonfly to explore both the surface and the atmosphere of Titan[6]. The proposed concepts are shown in Figure 1.

(a) (b)

Figure 1. (a) Dragonfly and (b) Montgolfiere balloon flagship[18,19].

The Montgolfiere balloon concept suggests continuing research in Titian exploration via balloons. Utilizing a helium enveloped design will allow for operation in the Titian atmosphere for long periods of time with minimal energy use due to the slow rate of diffusion. The balloon also allows for more gentle landings that would prevent any possible damage. A high payload capacity, as well as the ease of functionality of the balloon within the atmosphere, also makes it an attractive idea for Titan exploration. In 2016 Global Aerospace Corporation combined the helium balloon concept with a glider to develop the Titan Winged Aerobot, as presented in Figure 2. The Titan Winged Aerobot is identified as a hybrid entry vehicle and balloon glider that is capable of descent and ascent through the use of pumps or mechanical compressions. The glider had ultra-low power requirements, an extended vertical range, and 3D controlled maneuverability. Although the design is capable of low altitude flight, it does not have take-off capabilities. Unless the design was paired with a probe, the exploration would be limited to atmospheric analysis[19].

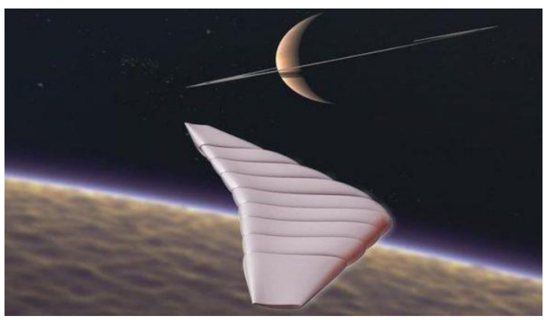


Figure 2. Titan winged aerobot developed by Global Aerospace Corporation[19].

A UAV drone mission concept for exploring Titan was proposed in 2012. The Aerial Vehicle for In-situ and Airborn Titan Reconnaissance (AVIATR) was to be nuclear powered which broadened the spectrum for possible research opportunities on Titan. The aircraft would rely on a focus on the exploration of Titan's global features including geology/hydrology and lower atmospheric structures[1,19]. The concept is shown in Figure 3.

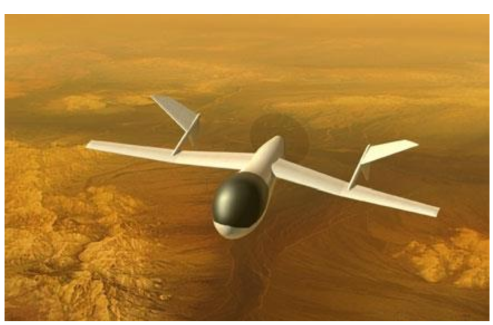


Figure 3. Schematic view of Aerial Vehicle for In-situ and Airborn Titan Reconnaissance (AVIATR)[19].

III. Titan Atmosphere Characteristics

Titan is the second-largest natural satellite with the most Earth-like atmosphere in the solar system[8]. The atmosphere consisted of 98.4% nitrogen, with the remaining 1.6% of methane and other gases such as hydrocarbons, carbon dioxide, carbon monoxide, argon, hydrogen cyanide, cyanogens, and helium. Therefore, Titan has the densest atmosphere among all natural satellites; at 5.44 Kg/m^3, is denser than Earth's[20]. The surface pressure is one and a half times that of Earth's at 147 KPa, but the surface temperature is quite low, about 94 K. Titan's thermospheric wind speed and acceleration due to gravity have been reported to be 60m/s and 1.354 m/s^2, respectively. In order to calculate the viscosity of the Titan atmosphere, the equation directed toward Earth's atmosphere can be applied because of the same dominate particles exist in both atmospheres. The dynamic viscosity of air is approximated as follow[21-24]:

$$\mu \approx 1.8325\times10^{-5}\left(\frac{416.16}{T+120}\right)\left(\frac{T}{296.16}\right)^{\frac{3}{2}} \qquad (1)$$

where μ and T denote Titan's atmospheric viscosity and temperature, respectively. Applying the temperature versus altitude graph for Titan, the viscosity versus altitude for Titan's atmosphere can be obtained. The temperature, pressure, density, and viscosity of the Titan's atmosphere at different altitudes are shown in Figures 4(a), 5(b), 5(c), and 5(d), respectively[1]. Both the temperature and viscosity decrease as the altitude approaches 50 km, and then steadily increase and the altitude rises. With the density and pressure of the Titan moon, they start high as the altitude is zero, and then exponentially decrease and approach zero as the altitude increases.

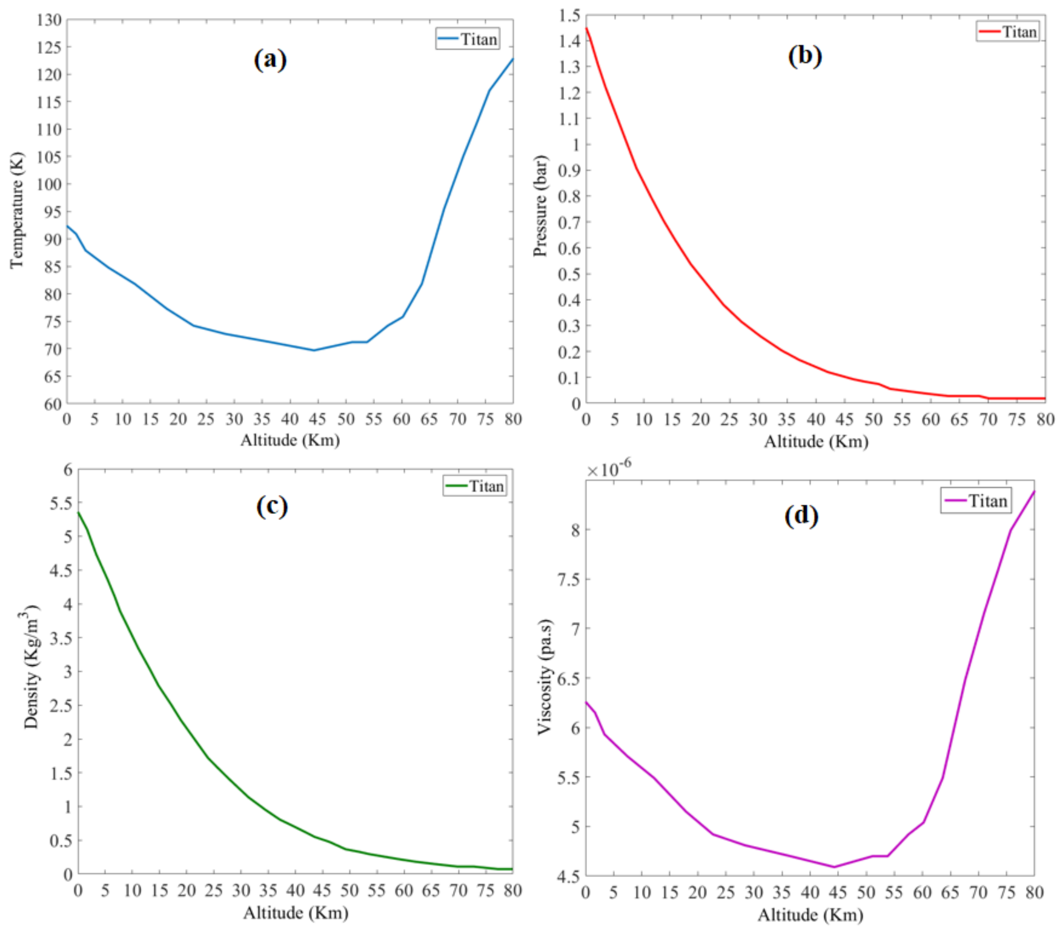


Figure 4. Average (a) temperature, (b) pressure, (c) density, and (d) viscosity of Titan atmosphere versus altitude[1].

As previously mentioned, one of the researchers' biggest draws to the Titan moon is the liquid methane lakes that, through the Cassini-Huygens mission, was found to cover around 2% of the moon as shown in Figure 5. This is such an astonishing phenomenon because it suggests that the moon has hydrologic cycles and may contain life within the depths of the lakes. Scientists have speculated as to how the lakes themselves have formed as well as maintain themselves throughout the years. It has been suggested that the lakes could have been created by liquid methane continually dissolving the moon's surface and possibly storing ethane at the bottom of the lakes. The lakes could also be kept up by liquid nitrogen rainfall within the hydrologic cycle, but the only way for scientists to confirm their theories is through actual experimentation and research within the moon[25].

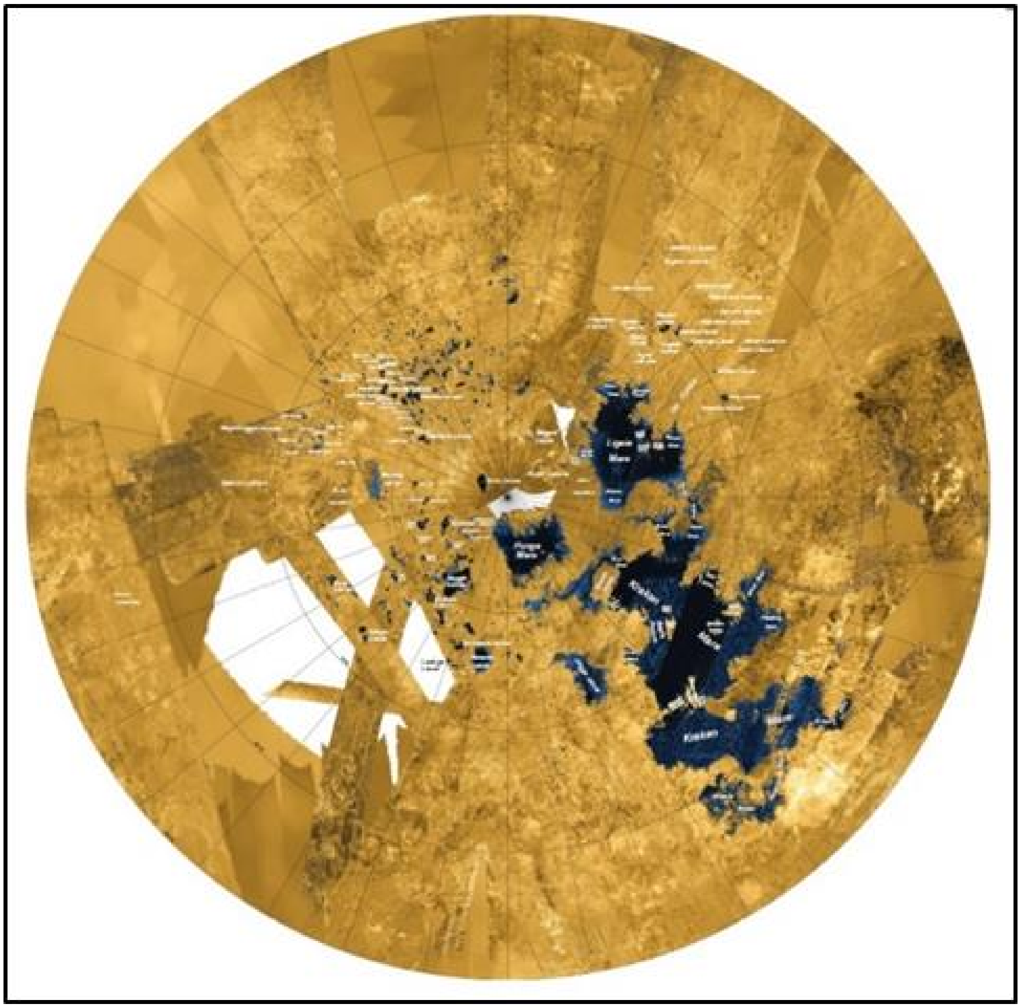
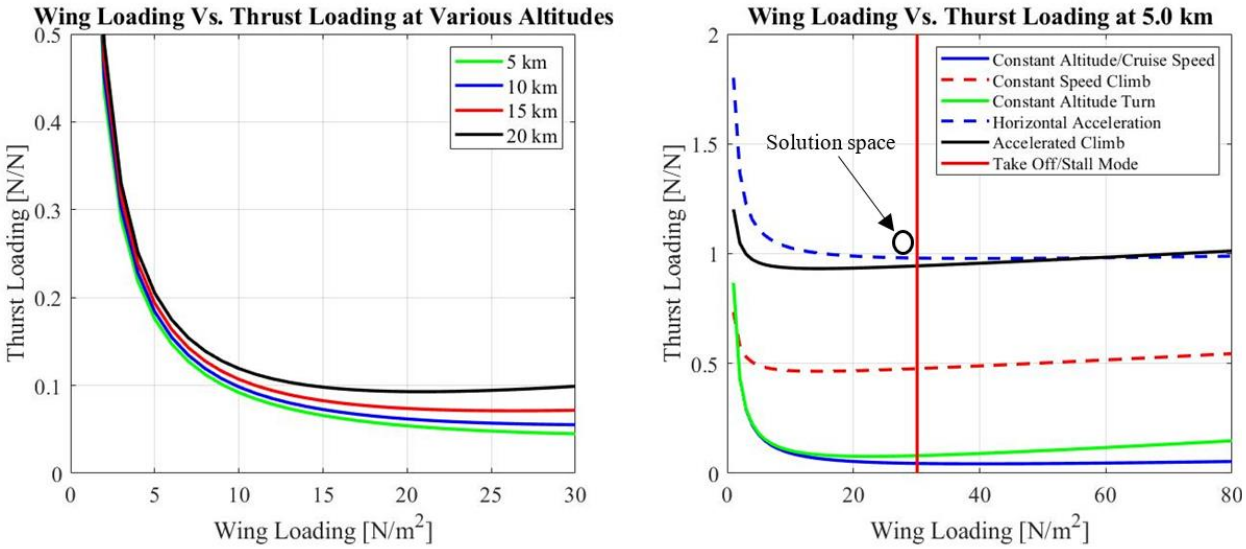


Figure 5. Elevated view of Titan's liquid methane lakes[26].

IV. Novel Drone Design

Titan's atmosphere is ideal for a fixed-wing unmanned aerial vehicle due to its high density and low gravity. Given the characteristics of Titan's atmosphere and the assumed mission presented above, constraint analysis was performed for an aspect ratio of 4. In order to identify the optimized altitude for flying, constraint analysis was performed on steady, cruising flight at various altitudes[27-30]. According to Figure 6(a), as altitude increases so does the thrust required for a given wing loading. Keeping in mind that lower altitudes are more ideal for planetary exploration, an altitude of 5km was chosen for further analysis. Figure 6(b) presents the constraint analysis and solution space of the system at an altitude of 5 km.



(a) **(b)**

Figure 6. Constraint analysis of (a) cruising flight at various altitudes and (b) six different flight modes at a 5 km altitude that provides the solution space for the optimal wing loading.

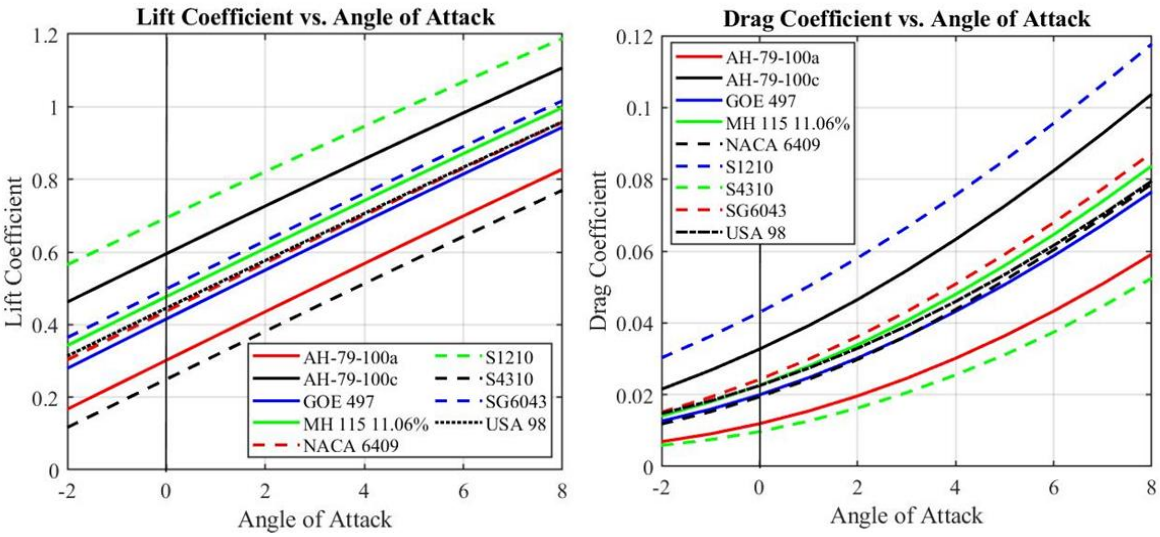
The solution space in Figure 6(b) provides the wing loading necessary for flight to be 30N/m^2. Through analysis of the weight distributions of various gliders with similar flight capabilities trying to be achieved such as the AAI RQ-7 Shadow[31], the estimated total weight of the drone is 270 N, with a structural, equipment, and fuel weight of 135 N, 67.5 N, and 67.5 N, respectively. With the wing loading and estimated weight of the aircraft, the planform area, wingspan, and mean area chord were determined to be 6.67 m^2, 5.17 m, and 1.3 m, respectively. In studying different types of wings, a tapered wing with a ratio of 0.3 was chosen based on its high efficiency and low induced drag. Therefore, a root chord of 1.97 m and a tip chord of 0.596 m was identified.

The next step in the design is to identify the airfoil of the wing[32]. The airfoils listed in Table 2 were chosen for analysis based on their max thickness percentage and max camber percentage.

Table 2. Airfoils considered for design.

Airfoil	Max Thickness (%)	Max Camber (%)
AH 79-100A	10	3.6
AH-79-100C	9.9	6.7
GOE 497	12.7	5.3
MH 115 11.06%	11.06	5.5
NACA 6409	9	6
SG6043	10	5.1
S1210 12%	12	6.7
S4310	10.9	4.2
USA 98	14.3	3.5

The airfoils from Table 2 were analyzed in the aircraft analysis software, XFLR5, to determine the optimal airfoil. The lift and drag coefficients are plotted versus angle of attack in Figures 7(a) and 7(b), below. Although it has the least amount of lift compared to the rest of the airfoils, the S4310 was chosen based it having the smallest drag coefficient at all angles of attack. Furthermore, given the equation of lift, noted below, solving the equation for lift coefficient for the density of Titan’s atmosphere, the required lift coefficient is 0.1304. According to Figure 7(a), the lift coefficient of the S4310 is sufficiently greater than that.



(a) (b)

Figure 7. Constraint analysis of (a) cruising flight at various altitudes and (b) six different flight modes at a 5 km altitude that provides the solution space for the optimal wing loading.

This design also will use Titan's liquid methane oceans to refuel its fuel tank. When the drone runs out of fuel it will land on the surface of a methane ocean and float while it obtains the methane necessary for its next flight. The drone will thus have two tanks mounted to the bottom of the wing mimicking the skids on the bottom of a seaplane. There will be a vacuum system that fills the tanks with the liquid methane of the oceans. Through the use of an oxidizer, the methane in the drone will be turned into the main source of power. There are different types of oxidizers that can be used for converting the liquid methane to energy, which are shown in Table 3.

Table 3. Oxidizers and phase change temperatures[1].

Oxidizer	Boiling point (C)	Freezing point (C)	Density (gm/cm^3)
Oxygen (O_2)	-183	-218.8	1.143
Fluorine (F_2)	-18.1	-219.6	1.505
Nitrogen Tetroxide (MON3) (N_2O_4)	21.2	-11.2	1.45
Chlorine Trifluoride (CLF_3)	11.8	-76.6	1.825
Inhibited Red Fuming Nitric Acid (IRFNA) ($0.835HNO_30.140NO_2$ $0.020H_2O0.005HF$)	60	-62.2	1.56
Oxygen Difluoride (OF_2)	-145	-223.9	1.521
Nitrogen Tetroxide (MON25) (N_2O_4)	-9	-54	1.45

As the combustion of liquid methane and liquid oxygen is frequently used as liquid rocket fuel, it is seen as the most advantageous propellant system. Given that methane has one of the highest specific impulses of hydrocarbon fossil fuels, the oxidation reaction provides a great alternative to solar energy for Titan exploration[33].

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (1)$$

Given that there is no oxygen on Titan, the length of the mission will be limited to the amount of liquid oxygen that can be transported on board the drone. However, due to the advantageous flight conditions, the power required to propel the drone is low. Furthermore, with an expansion ratio of 1:861 for oxygen and a mixing ratio of one-part oxygen to 3.2 parts liquid methane, it is anticipated that such system is capable of flying up to ten days between oceans and have a total lifespan of nearly 75 days[33-35]. Further research must be conducted on the implementation of a Methane/LOX engine including how the system will be refueled. A summary of the proposed concept characteristics is noted in Table 4 and the design is shown in Figure 8.

Table 4. Characteristics of fixed-wing UAV for Titan exploration.

Characteristic	Value
Wing type	Tapered
Aspect ratio	4
Taper ratio	0.3
Wingspan	5.17 m
Planform area	6.67 m^2
Total weight	270 N
Wing loading	30 N/m^2
Thrust loading at altitude	0.05 N/N
Airfoil	S4310
C_L minimum at zero angle of attack	0.13
C_L of wing at zero angle of attack	0.25
C_D of wing at zero angle of attack	0.01
C_L/C_D of wing at zero angle of attack	25.7

Figure 8. Schematic view of Titan-based fixed-wing drone.

V. Conclusion

Having a similar atmosphere to Earth's, the possibilities of employing a space drone for further exploration of Saturn's largest moon, Titan, is explored. Through studying the atmospheric characteristics and other related concepts, a conceptual drone that utilizes Titan's methane oceans as a fuel supply for repeatable flight will be designed. The proposed methane fuel supply may be applied to future drones and even in larger-scaled aircrafts performing research missions on Titan. Future work for this project includes further investigation of the liquid methane refueling system, the liquid methane/liquid oxygen propulsion system, control mechanisms, and structural analysis and material integrity in the environments of Titan.

Acknowledgment

The authors Mostafa Hassanalian and Victoria Pellerito gratefully acknowledge the financial support from the National Science Foundation. This study was supported by the INTENSE REU program. The INTENSE REU is funded by the National Science Foundation (NSF) Division of Engineering Education and Centers (EEC) award #1757793. The project is led at New Mexico Tech by PI Dr. Michael Hargather and Co-PI Dr. Mostafa Hassanalian.

The author Micaela Olivas gratefully acknowledges the financial support from the New Mexico Space Grant Consortium.

References

[1]Hassanalian, M., Rice, D. and Abdelkefi, A., "Evolution of space drones for planetary exploration: a review", *Progress in Aerospace Sciences*, Vol. 97, pp.61-105, 2018.

[2]Hassanalian, M., Rice, D., Johnstone, S., Abdelkefi, A., "Performance analysis of fixed wing space drones in different solar system bodies", *Acta Astronautica*, Vol. 152, pp.27-48 , 2018.

[3]Acosta, G.A., Grow, D. and Hassanalian, M., "Design and Analysis of a High Pressure and High Temperature Fixed Wing Space Drone for Venus Exploration", 2019 AIAA Aviation Forum, Dallas, TX, 17-21 June, 2019.

[4]Hassanalian, M., Rice, D., Abdelkefi, A., "Aerodynamic performance analysis of fixed wing space drones in different solar system bodies", 2018 AIAA Aerospace Sciences Meeting, Kissimmee, Florida, 8–12 January 2018.

[5]Hassanalian, M., Rice, D., Johnstone, S., Abdelkefi, A., "Planetary exploration by space drones: design and challenges", 2018 AIAA Aviation Conference, Atlanta, Georgia, 25-29 June 2018.

[6]Maxwell, A., Acosta, G.A., Ward, M., Hamm, A. and Hassanalian, M., "Cleaning Mechanisms for Solar Panels of Rovers and Other Extraterrestrial Unmanned Vehicles", 2019 AIAA Aviation Forum, Dallas, TX, 17-21 June, 2019.

[7]Lemke, L.G., Heldmann, J.L., Young, L.A., Gonzales, A.A., Gulick, V.C., Foch, R.E., Marinova, M.M. and Gundlach, J.F., "Vertical Takeoff and Landing UAVS for Exploration of Recurring Hydrological Events", In Concepts and Approaches for Mars Exploration, Vol. 1679, June 2012.

[8]Sappington, R.N., Acosta, G.A., Hassanalian, M., Lee, K. and Morelli, R., "Drone Stations in Airports for Runway and Airplane Inspection Using Image Processing Techniques", In AIAA Aviation 2019 Forum, Dallas, Texas, 17-21 June 2019.

[9]Mirzaeinia, A., Hassanalian, M., Shekaramiz, M. and Mirzaeinia, M., "Loader and tester swarming drones for cellular phone network loading and field test: non-stochastic particle swarm optimization", Journal of Autonomous Intelligence, Vol. 2, No. 2, pp.14-24, 2019.

[10]Mirzaeinia, A., Hassanalian, M., Lee, K. and Mirzaeinia, M., "Energy conservation of V-shaped swarming fixed-wing drones through position reconfiguration", *Aerospace Science and Technology*, Vol. 94, p.105398, 2019.

[11]Mirzaeinia, A. and Hassanalian, M., "Minimum-Cost Drone–Nest Matching through the Kuhn–Munkres Algorithm in Smart Cities: Energy Management and Efficiency Enhancement", *Aerospace*, Vol. 6, No. 11, p.125, 2019.

[12]https://solarsystem.nasa.gov/moons/saturnmoons/titan/exploration/?page=0&per_page=10&order=launch_date+desc%2Ctitle+asc&search=&tags=Saturn&category=33#dutch-astronomer-christiaan-huygens-discovers-titan

[13]https://solarsystem.nasa.gov/missions/cassini/science/titan/

[14]Guido, N., Mohammadi, S., Hassanalian, M. and Bakhtiyarov, S., "Surface Temperature Effects of Solar Panels of Fixed Wing Unmanned Aerial Vehicles on Flight Performance", 2019 AIAA Aviation Forum, Dallas, TX, 17-21 June 2019.

[15]Hassanalian, M., Radmanesh, M., Sedaghat, A., "Increasing flight endurance of MAVs using multiple quantum well solar cells", *International Journal of Aeronautical and Space Sciences*, Vol. 15, No. 2, pp.212-217, 2014.

[16]Hendrix, A.R. and Yung, Y.L., “Energy Options for Future Humans on Titan”, *arXiv preprint arXiv:1707.00365*, 2017.

[17]https://solarsystem.nasa.gov/moons/saturn-moons/titan/overview/

[18]https://phys.org/news/2017-05-titan-ripe-drone-invasion.html

[19]http://www.astronomy.com/news/2017/03/titan-aerial-platforms

[20]https://en.wikipedia.org/wiki/Titan_(moon)

[21]Hassanalian, M., Abdelmoula, H., Ben Ayed, S., Abdelkefi, A., “Thermal impact of migrating birds’ wing color on their flight performance: Possibility of new generation of biologically inspired drones”, *Journal of Thermal Biology*, Vol. 66, pp. 27–32, 2016.

[22]Alexander, J. S, and Dussauge, J.P., “Turbulent shear layers in supersonic flow”, Birkhäuser, 2006.

[23]Hassanalian, M., Ben Ayed, S., Ali, M, Houde, P., Hocut, C., Abdelkefi, A., “Insights on the wing colorization of migrating birds on their skin friction drag and the choice of their flight route”, *Journal of Thermal Biology*, Vol. 72, pp. 81-93, 2018.

[24]Hassanalian, M., Throneberry, G., Ali, M., Ben Ayed, S., Abdelkefi, A., “Role of wing color and seasonal changes in ambient temperature and solar irradiation on predicted flight efficiency of the Albatross”, *Journal of Thermal Biology*, Vol. 71, pp. 112-122, 2017.

[25]https://www.nasa.gov/feature/jpl/cassini-explores-a-methane-sea-on-titan

[26]https://en.wikipedia.org/wiki/Lakes_of_Titan

[27]Hassanalian, M., Abdelkefi, A., Wei, M., Ziaei-Rad, S., “A novel methodology for wing sizing of bio-inspired flapping wing micro air vehicles: theory and prototype”, *Acta Mechanica*, Vol. 228, No. 3, pp.1097-1113, 2017

[28]Hassanalian, M., Salazar, R. and Abdelkefi, A., “Conceptual design and optimization of a tilt-rotor micro air vehicle”, *Chinese Journal of Aeronautics*, Vol. 32, No. 2, pp.369-381, 2019.

[29]Hassanalian, M. and Abdelkefi, A., “Design, manufacturing, and flight testing of a fixed wing micro air vehicle with Zimmerman planform”, *Meccanica*, Vol. 52, No. 6, pp.1265-1282, 2017.

[30]Hassanalian, M., Quintana, A., and Abdelkefi, A., “Morphing micro unmanned air vehicle: sizing process and stability”, Aerospace Science and Technology, Vol. 78, pp. 130-146, 2018.

[31]https://en.wikipedia.org/wiki/AAI_RQ-7_Shadow

[32]Hassanalian, M., Khaki, H., Khosrawi, M., “A new method for design of fixed wing micro air vehicle”, *Proceedings of the institution of mechanical engineers, Part G*, Vol. 229, pp. 837-850, 2014.

[33]http://www.braeunig.us/space/propel.htm

[34]https://www.benjaminmunro.com/liquid-oxygen-methane-engine-development

[35]Yatsutanagi, N., “Comprehensive Design Method for LOX/Liquid-Methane Regenerative Cooling Combustor with Coaxial Injector”, *Transactions of the Japan Society for Aeronautical and Space Sciences*, Vol. 52, No. 177, pp. 180–187, 2009.