Aerodynamic Performance of Advanced Ingenuity and Dragonfly Drones for Future Space Missions to Mars and Titan

Osama W. Ata
Dept. of Electrical Engineering
Palestine Polytechnic University
Hebron, State of Palestine
oata@fulbrightmail.org

2021 4th International Symposium on Advanced Electrical and Communication Technologies (ISAECT) | 978-1-6654-3773-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/ISAECT53699.2021.9668399

Abstract— **The future of space missions to habitable Mars and Saturnian moon; Titan, is very promising to mankind as far as sending coaxial rotorcrafts or dual-quadcopter landers, to fly in their atmospheric extremes, are concerned. The aerodynamic performance of Martian Ingenuity is compared to that on Titan and Earth. Advanced design features of Ingenuity are further explored and analyzed that resulted in added benefits of increased hover time, range with a payload of about 28% of its gross weight. The enhanced performance of the advanced design would move its role from a helicopter demonstrator to a helicopter assistant of a landed rover with exploration and excavation tasks to perform in dune caves and volcano craters. Further, the performance of a dual-quadcopter lander; Titanean Dragonfly, is explored and compared to that on Earth. The relatively denser atmosphere and lower gravitational acceleration offer favorable flying conditions for rotorcrafts that can save on power consumption if the equipment is further fortified against the extremely cold temperature on Titan.**

Keywords — Mars, Titan, Ingenuity, Dragonfly, rotorcraft, aerodynamics, lift force, atmospheric density, battery capacity.

I. INTRODUCTION

Man has been yearning to discover Mars for many decades. Mars, after Earth, is the most habitable planet in our solar system due to several reasons. For a start, it is a solid and not a gaseous planet. Gravity [1] on Mars is 38% of that on our Earth, which is believed to be sufficient for the human body to adapt to. It also has an atmosphere, though a very thin one; around 1% [1] of that on Earth, which predominantly offers protection from cosmic and the Sun's radiation. Mars is a very cold and dry planet, unlike the lead-melting temperature of Venus, with an average temperature of -60^0 C and -125^0 C near its poles.

There are a number of reasons to travel to Mars. The first is the realization of an amazing dream. Sending a manned mission to Mars is a fantastic adventure. Those who observed Neil Armstrong land on the Moon several years ago do still remember every detail; where they were, who they were with and how they felt. The moment the first astronauts land on Mars will be our historical moment to remember and treasure. A second reason is endless curiosity. Where did Mars come from? Can it teach us about Earth's history? Is there life on Mars? These are just a few burning questions for scientists all over the world. A third reason would be progress. Sending astronauts on Mars would be "the next giant leap for mankind" to explore its resources and realize other massive developments in several areas of human interest.

Flying a drone or a helicopter on Mars has engaged the curious minds of scientists and engineers, predominantly because of its very thin atmospheric density and very cold temperature challenges, in addition to its extremely remote distance from Earth. If a drone could successfully operate on Mars, it would act as a scout, checking the land ahead of a rover to confirm safety to travel. Such an aircraft would even assist in the search for water and life on the Martian surface. It is expected, in 2035 [2] that man would eventually land on Mars.

The first use of a rotorcraft for a planetary mission; on Mars, has been demonstrated on April 19, 2021, when Ingenuity was deployed from Perseverance [3]. "The goal of the Ingenuity, shown in Figure 1, was to demonstrate the potential of flying vehicles in the Martian atmosphere. Ingenuity is a coaxial helicopter with a mass of 1.8 kg and rotor diameter of 1.21 m. The helicopter relies on solar cells and a battery system for power, allowing up to 90 second flight endurance that must be conducted fully autonomously due to the long communication signal delay; of 3 and 22 minutes, depending on the changing distance with time between Earth and Mars".

As a demonstrator, Ingenuity has flown 9 times, so far, for more than 70 seconds and 160 meters, over relatively flat, rock-free terrain and using a visual-inertial navigation system. The realization of the Martian drone performance would lead to improve the design of a larger drone, capable of carrying payloads "that can be used as onboard science instruments intended for soil digging, mapping, stratigraphy and remote sensing, with an extended range (2–4 km) and increased hover time (2–4 minutes)", sufficient to enable significant science investigations both in flight as well as when on the surface.

On a different front, scientists have turned their eyes on Saturn; which is the least dense planet in the solar system, predominantly composed of hydrogen and helium and bears traces of ices containing ammonia, methane, and water. Saturn [4] has 82 moons. "Fifty-three moons are confirmed and named and another 29 moons are awaiting confirmation of discovery and official naming". Saturn's largest moon is Titan [5] which stands out as a strong candidate for habitability. "Titan's diameter is 50 percent larger than Earth's Moon, making it among the largest natural satellites in the solar system. Titan's most obvious feature is its heavy, hazy atmosphere. The most abundant gas is nitrogen, with methane and ethane clouds".

Titan was discovered in 1655 by Dutch astronomer Christiaan Huygens [5]. It was named after the ancient race

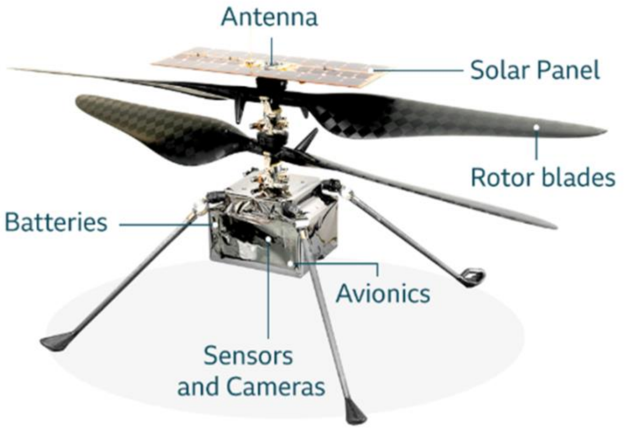

Fig. 1. The Martian coaxial rotorcraft; Ingenuity (Courtesy to NASA)

of giants in Greek Mythology. The composition of Titan is known to be water ice over a rocky interior. Its surface has liquid hydrocarbon lakes and is thought to have several layers: a rocky core, surrounded by layers of crystalline ice. It is likely that the core is still hot, with a layer of liquid water and ammonia. Several probes have imaged Titan, but only one has visited the surface; the Huygens lander. It arrived on January 14, 2005, and sent data for about an hour and a half, making it the most distant landing of any mission in the solar system.

Interestingly, Titan has an atmospheric density [6] which is 4.4 times that of Earth, on sea level. Its gravity is 1/7 of that on Earth. It has a mean surface temperature of -180^0 C. Conceptually, the atmospheric density and gravity of Titan make it much less challenging to fly a drone or a helicopter on Earth and significantly less challenging to fly it on Mars. Because of the relatively high atmospheric density, the desired lifting force of a rotorcraft could be obtained for less kinetic energy produced by comparative rotor blades. This means that there could be a higher potential benefit of landing a rotorcraft by a parachute on Titan than landing a rover on Mars. A rotorcraft can cover larger distances in relatively shorter times, can reach and travel between high dunes and can avoid dangerous landscapes, as opposed to a rover, while carrying the necessary science instruments for exploration.

There are three objectives for this work. The first objective is to demonstrate a comparative aerodynamic performance study of Ingenuity rotorcraft on Mars, Earth and Titan. The second objective would be to analyze the aerodynamic performance of an advanced design for Ingenuity, on Mars, which would carry a science payload, relatively hover a larger time and cover a longer range. That would act as an Assistant to any future rover lander to help on certain science missions, like exploring wide caves in Martian mountains or obtaining soil or rock samples from craters. Since such a rotorcraft would be battery operated, the hover time and range would be analyzed for reduced payloads with swapped batteries. The advanced design is assumed to be less than 5 kg, since the thin atmosphere of Mars, combined with the diameter limitation of the heat-shielded capsule, parachuting a rover with a rotorcraft in its belly, would present strict size and weight limitations on any future advanced Martian rotorcraft. The third objective would be to analyze the performance of Dragonfly [6], shown in Figure 2, a dual quadcopter on Titan, estimated to be 420 kg that would replace a rover in such favorable atmospheric conditions. Interestingly, “Dragonfly will not be equipped with a robotic arm, like the recent Mars rovers. Its exploration will first be guided by an instrument on its belly that will bombard the ground with neutron radiation that releases gamma rays, to differentiate between basic terrain types, such as ammonia-rich ice or carbon-rich sand dunes. Its two landing skids will also each carry a rotary-percussive drill capable of taking samples and feeding them through a pneumatic tube to a mass spectrometer that can analyze their composition” [7].

This paper is organized in the following sections: Abstract, introduction, conceptual design, methodology, results, discussion of results and conclusion.

II. CONCEPTUAL DESIGN

Ingenuity is powered by a Li-Ion battery system that is recharged daily by a solar panel. The energy in the battery is used for operating heaters to survive the cold Martian nights as well as operate the helicopter actuators and avionics during short flights lasting from 90 seconds to a few minutes. “Depending on the latitude of operations and the Martian season, recharging of this battery through the solar panel could occur over one to multiple sols (Martian days). The helicopter battery consists of 6 Sony SE US18650 VTC4 [3,8] Li-ion cells with a nameplate capacity of 2 Ah. The battery voltage is in the range of 15–25.2 V and the total mass of the 6 cells is 273 g. A de-rated end-of-life battery capacity of 35.75 Wh is available for use. Of this capacity, 10.73 Wh (30%) is kept as reserve, night-time survival energy usage is estimated at 21 Wh for typical operation in the northern latitudes in the spring season, and approximately 10 Wh is available for flight”.

The solar panel is made from “Inverted Metamorphic (IMM4J) cells from SolAero Technologies” [9]. “The cells are optimized for the Mars solar spectrum and occupy a rectangular area with 680 cm^2 of substrate (544 cm^2 active cell area) in a region centered and immediately above the co-axial rotors”.

Ingenuity features four specially made carbon-fiber blades [10], arranged into two rotors that spin in opposite directions at around 2,500 rpm. The blades weigh a total of 70 grams. The design variables used in the design of the coaxial helicopter were: rotor radius 0.605 m, number of rotor blades 4, blade width 0.1 m, gross weight 1.8 kg, total power 0.36 kW, battery capacity 12 Ah.

The lift and drag equations [11] that determine the lift and drag forces acting on the rotorcraft can be expressed as:

$$L = \frac{1}{2} C_L n \rho A v^2 \tag{1}$$

Where, L is the lift force (Newton)

C_L [12] is the lift coefficient (0.977)

n is the number of rotor blades (4)

ρ is the atmospheric density (kg/ m^3)

A is the area of the blade (radius x width in m^2)

v is the linear tip velocity of the rotor (m/s)

And the drag coefficient can be expressed in a similar way in the following equation:

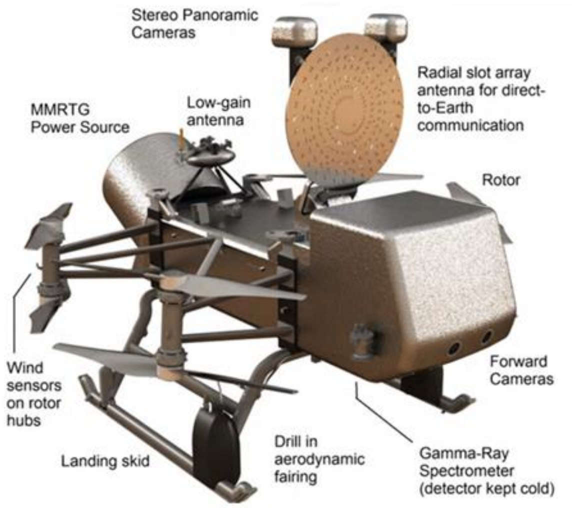

Fig. 2. The Titanean dual quadcopter lander; Dragonfly (Courtesy to NASA)

$$D = \frac{1}{2} C_D n \rho A v^2 \quad (2)$$

Where, D is the drag force (Newton)

C_D [12] is the drag coefficient (0.0243)

Now

Flight Energy = Thrust Energy + Rotational Energy + Translational Energy + Potential Energy

That is

$$E_f = E_T + \frac{1}{2} I \omega^2 + \frac{1}{2} M v^2 + M g h \quad (3)$$

where, $E_T = T v_r t = D v_r t$

T is the thrust force (Newton)

v_r is the rotor linear velocity (m/s)

t is hover time in (s)

I is the moment of inertia (assumed to be $mr^2/3$)

m is the total mass of the 4 blades (70 g)

r is the rotor radius (0.605 m)

w is the rotor angular velocity (rad /s)

M is the weight of the rotorcraft (kg)

v is the translational velocity (m/s)

g is the gravitational acceleration (m/s^2)

h is the average flight height (m)

TABLE 1.ATMOSPHERIC DENSITY AND GRAVITATIONAL ACCELERATION OF MARS, EARTH AND TITAN

Planet/ Saturnian moon	Atmospheric density (kg/m^3)	Gravitational acceleration (m/s^2)
Mars	0.017	3.724
Earth	1.225	9.8
Titan	5.4	1.35

TABLE 2.COMPARATIVE DESIGN FEATURES OF MARTIAN INGENUITY AND ADVANCED ROTORCRAFT

Feature	Unit	Ingenuity	Advanced rotorcraft
Gross weight	kg	1.8	4.6
Payload	kg	0	1.3
Cruise speed	m/s	2	30
Hover time	min	1.5	2
Total power	kW	0.36	0.88
Battery capacity	Ah	12	48

Table 1 compares the atmospheric density and gravitational acceleration of Mars, Earth and Titan. These would affect the aerodynamic performance, and consequently the rpm speed of the rotorcraft blades.

Table 2 compares some of the improved design features of the advanced rotorcraft to those of Ingenuity. Both are coaxial rotorcrafts, number of blades = 4, and blade radius = 0.605 m, blade area= 0.0605 m^2.

Table 3 shows some of the improved design features of Titan Dragonfly. Dragonfly is an 8-bladed dual quadcopter, blade radius = 0.5 m, and blade area= 0.05 m^2. The lift and drag coefficients, in the design, were conservatively considered $C_L = 0.5$ and $C_D = 0.04$, respectively.

Figure 2 shows Dragonfly; a dual quadcopter and a rotorcraft lander that is due to be launched on the Saturn moon; Titan in 2027 and expected to land in 2036 [13].

III. METHODOLOGY

A simple program was developed, utilizing the design features of Ingenuity, to calculate the variation of the cruise speed with payload and compare the aerodynamic performance of the rotorcraft on Mars, Earth and Titan. The altitude of the cruising drone was assumed 5 m at which the cruise speed was 2 m/s without any payload. The atmospheric features of each planet / Saturnian moon were considered in the analysis. The hover time, for each payload was considered to be 1.5 minutes. Hence a reduction in the cruise speed would result in a reduction in the maximum range.

In regard to the advanced rotorcraft, hover time and range were calculated for a number of payloads and compared to Ingenuity on Mars. Initially, the gross weight of 4.6 kg which included the 1.3 kg payload was considered at a fixed cruise speed of 30 m/s. For any reduced payload, an equivalent weight of batteries was substituted in order to assess the increased hover time and range.

TABLE 3. SOME DESIGN FEATURES OF TITAN DRAGONFLY ROTORCRAFT LANDER

Feature	Unit	Dragonfly lander
Mass	kg	420
Max range	km	60
Max Cruise speed	m/s	10
Max hover time	min	120
Range per flight	km	8
Time per flight	min	16
Power output	W	70
Power source	Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)	

The hover time calculation depends on the battery capacity and the average drawn current. For a relatively larger hover time, the rate of discharge may be slightly reduced for larger endurance. The effects of the battery discharge rate, as well as voltage drop, on the effective capacity were examined by [14].

In regard to the advanced rotorcraft, hover time and range were calculated for a number of payloads and compared to Ingenuity on Mars. Initially, the gross weight of 4.6 kg which included the 1.3 kg payload was considered at a fixed cruise speed of 30 m/s. For any reduced payload, an equivalent weight of batteries was substituted in order to assess the increased hover time and range. The hover time calculation depends on the battery capacity and the average drawn current. For a relatively larger hover time, the rate of discharge may be slightly reduced for larger endurance. The effects of the battery discharge rate, as well as voltage drop, on the effective capacity were examined by [14]. It was shown that the so-called Peukert effect can increase the range and endurance of a vehicle if the battery capacity is large with respect to the current required. Conversely, effective capacity is reduced if the current draw is close to the batteries' nominal capacity. Nevertheless, the carried payload and relatively increased cruise speed of the advanced rotorcraft, in comparison to Ingenuity, would merit it as a truly effective assistant for any future launched rover to Mars.

As far as Dragonfly, the special rotorcraft is designed to replace rovers, benefitting from the relatively high atmospheric density and low gravitation acceleration on Saturn moon; Titan. Cruise speed, rotor speed, fly altitude and payload effect were all assessed and compared to an equivalent rotorcraft on earth.

In all computations, the drag and lift coefficients for Advanced Ingenuity were kept constant as they depend on the geometry of the blades and the angle of attack. The angle of attack was not changed and was assumed to be low; within 2 degrees. The results need be verified experimentally by building those models and experimentally measuring their aerodynamic performance in specially customized chambers that mimic the atmospheric density and gravity of the particular planet / Saturnian moon.

IV. RESULTS

Figure 3 compares the aerodynamic performance of Martian Ingenuity in the three different atmospheres of Mars, Earth and Titan. The battery and flight altitude were kept constant and the speed of the rotor blades were 2500 rpm at cruise speed of 2 m/s. It is shown that, on Titan, Ingenuity would have a wider range of payload since the former has relatively the densest atmosphere and the lowest gravitational acceleration.

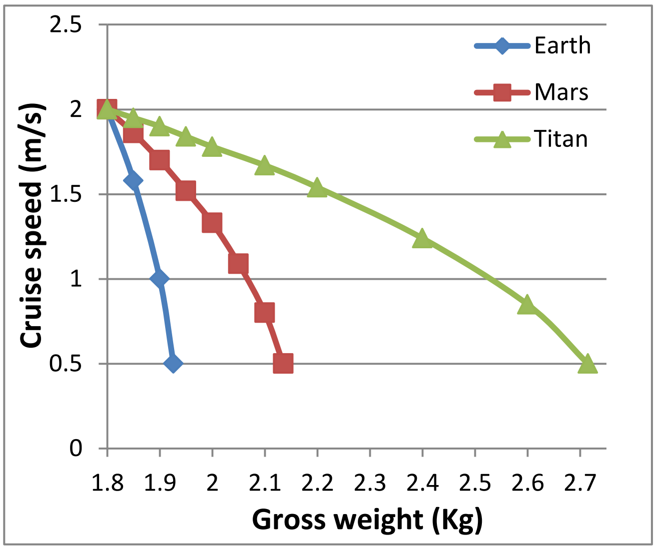

Fig. 3. Cruise speed versus gross weight of Ingenuity

Figure 4 shows substitute payload (kg), battery capacity (Ah/100) and cruise speed (km/min) versus hover time (min) obtained from calculated battery capacity and average current drawn. The cruise speed which is modeled by a smooth quadratic equation is based on the discharge rate drawn, with respect to the changed battery capacity. For a constrained geometry and a fixed battery weight, as a fraction of the total aircraft weight, increasing battery capacity reduces performance, and hence cruise velocity, due to greater required power and, consequently, current draw, which outweighs the capacity increase.

Figure 5 demonstrates the energy capacity distribution, designed for various substitute battery capacities. The energy of the battery unit distributed to supply its share for flight heat preservation for sustainable supply in the extremely cold nights of Mars and Titan.

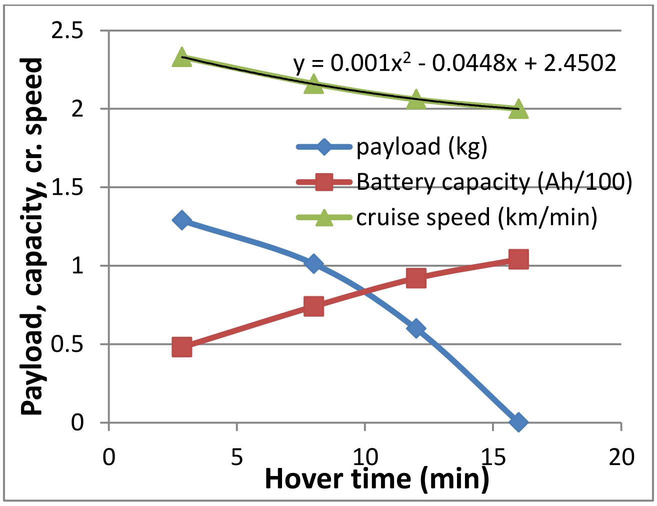

Fig. 4: Payload, battery capacity and cruise speed versus hover time

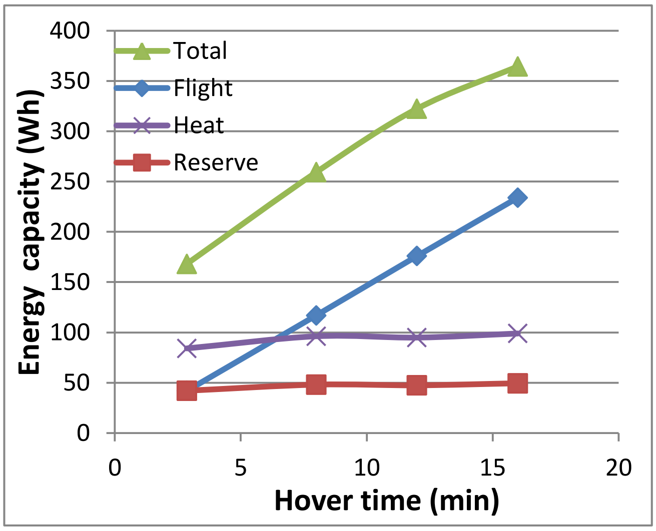

Fig. 5. Energy capacity (Wh) versus hover time (min)

Figure 6 demonstrates hover time versus range of Advanced Ingenuity for a various payloads. In comparison, the advanced helicopter, with no payload, has at least 10 times the hover time of Ingenuity and more than 175 times the relative range. Likewise, with less than 1 kg of payload, hover time is more than 3 times that of Ingenuity and range is relatively more than 60 times.

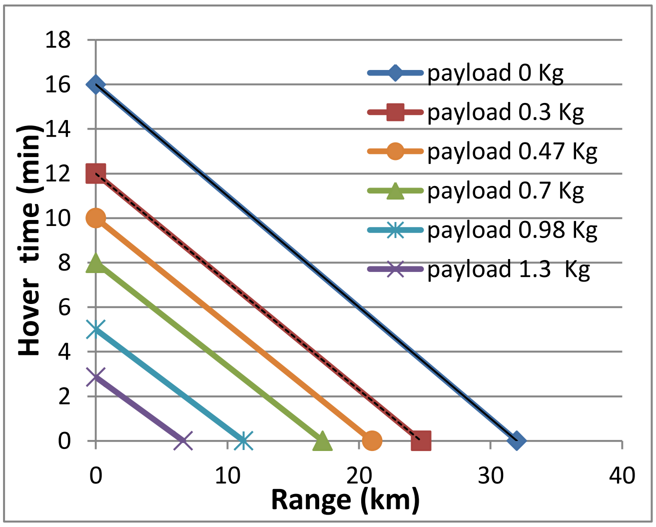

Fig. 6: Hover time versus range of Advanced Ingenuity for a range of payloads

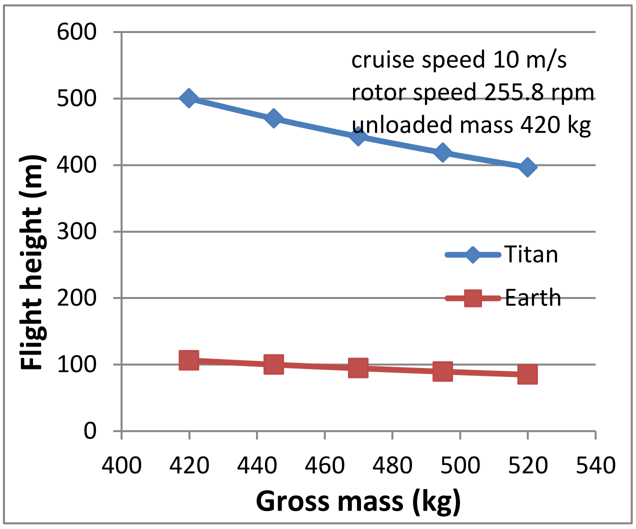

Fig. 7. Flight height versus gross mass performance of Dragonfly on at fixed rotor and cruise speeds

Figure 7 compares the flight height versus gross weight of Dragonfly on Titan and earth at a maintained rotor and cruise speeds and up to 100 kg of payload.

Figure 8 compares the cruise speed versus gross weight of Dragonfly at a maintained rotor speed of 200 rpm and height of 90 m on Titan and Earth. Figure 9 compares rotor speed versus gross mass at a maintained cruise speed of 10 m/s and flight height of 90 m.

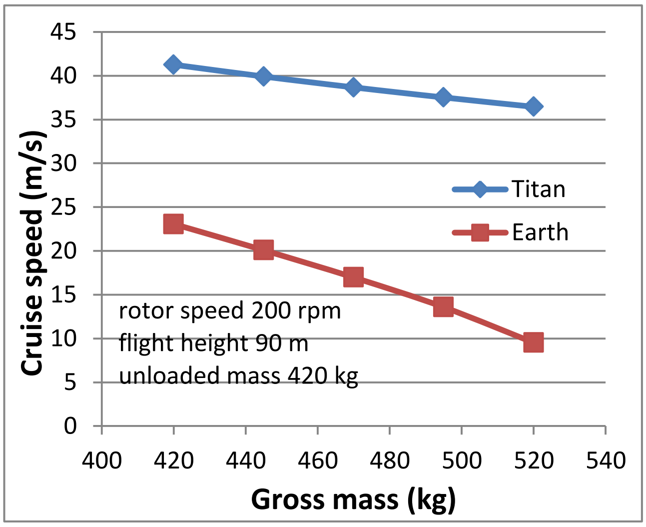

Fig. 8. Cruise speed versus gross mass of Dragonfly for a fixed rotor speed and flight height

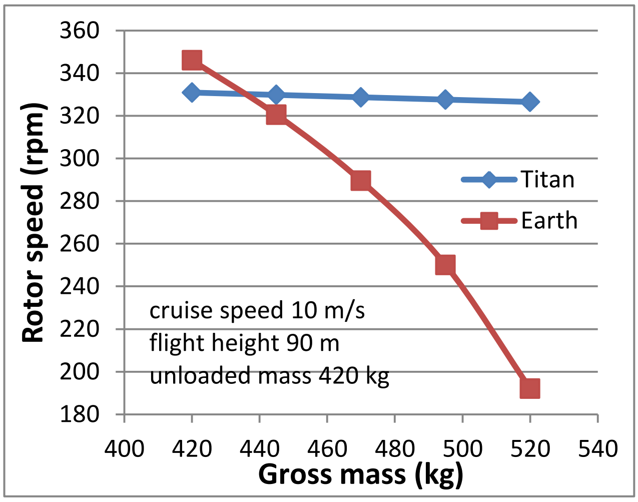

Fig. 9. Rotor speed versus gross mass of Dragonfly for a fixed cruise speed and flight height

V. DISCUSSION OF RESULTS

The cruise speed versus payload performance of Ingenuity was shown in Figure 3 in the atmospheric extreme conditions of Mars and Titan, compared to Earth. Mars offers very challenging conditions for rotorcrafts while Titan offers most favorite ones. With a zero payload, 5 m flight height and 2 m/s of cruise speed, the rotor speed of Ingenuity on Mars, Earth and Titan worked out as 2500.5 rpm, 602.1 rpm and 367.5 rpm, respectively. As for payload, Ingenuity could carry 0.915 kg on Titan, 0.335 kg on Mars and 0.125 kg on Earth before its cruise speed would drop down to ¼ of its unloaded speed.

With regard to the Advanced Ingenuity rotorcraft, the difference in the decreased payload is equivalent to the increased substitute of the added batteries and hence a consequent increase in the battery capacity. Here the Peukert's effect would kick in. Accordingly, the discharge rate of the battery decreases as the capacity relatively increases. With a constant flight altitude, the efficiency and available power of the propeller engine would proportionally decrease, with the discharge rate, leading to a relative decrease in the cruise velocity. Figure 4 shows the modeled cruise speed as a smooth quadratic equation.

The hover time, for different battery capacities can be calculated. It depends on the flight energy capacity, as shown in Figure 5. The battery needs to maintain a certain energy reserve proportion, in addition to heating energy, so that it would survive the extremely cold night of Mars. The different ranges, with different payloads, as shown in Figure 6, can be calculated from the associated hover times and cruise speeds. Figures 7-9 demonstrate the aerodynamic performance of the dual-quadcopter lander; Dragonfly, on Titan, compared to Earth. On Titan, the half-ton rotorcraft demonstrates relatively higher flight heights, higher cruise speeds and a fairly stable rotor speed, compared to Earth, for a range of payloads, up to 100 kg. With a mere 70 W source for such rotorcraft, Titan incurs much more favorable aerodynamic conditions than on Earth.

VI. CONCLUSION

In this paper, I demonstrated a quantitative analysis of the aerodynamic performance of Ingenuity on Mars, Earth and Titan. I developed the analysis to realize the potential of flying an advanced rotorcraft on Mars that could hover longer times, fly longer ranges and carry payloads that would qualify it as a true assistant, as opposed to a mere demonstrator, for future launched rovers on Mars. On a different front, flying an autonomous rotorcraft lander on Titan that would carry out all missions instructed to a rover would be a historical giant leap for man to witness by 2036.

REFERENCES

[1] W.J. Koning, W. Johnson, and H.F. Grip, "Improved Mars helicopter aerodynamic rotor model for comprehensive analyses," AIAA Journal, vol. 57, no. 9, 2019, pp. 3969-3979.

[2] E. Howell, "NASA Aims for Mars Landings in 2035 While Building Support for Lunar Gateway", Space, Oct 22, 2019. https://www.space.com/nasa-aims-for-2035-mars-landings-iac.html

[3] B. Balaram, T. Canham, C. Duncan, H.F. Grip, W. Johnson, J. Maki, A. Quon, R. Stern,. and D. Zhu, "Mars helicopter technology demonstrator," In 2018 AIAA Atmospheric Flight Mechanics Conference, Jan 2018, pp. 1-18.

[4] NASA Science, "Saturn Moons", Solar System Exploration. https://solarsystem.nasa.gov/moons/saturn-moons/overview/?page=0&per_page=40&order=name+asc&search=&placeholder=Enter+moon+name&condition_1=38%3Aparent_id&condition_2=moon%3Abody_type%3Ailike

[5] NASA Science, "Titan", Solar System Exploration. https://solarsystem.nasa.gov/moons/saturn-moons/titan/in-depth/

[6] R.D. Lorenz, E.P. Turtle, J.W. Barnes, M.G. Trainer, D.S. Adams, K.E. Hibbard, C.Z. Sheldon, K. Zacny, P.N. Peplowski, D.J. Lawrence and M.A. Ravine, "Dragonfly: A rotorcraft lander concept for scientific exploration at Titan," In Johns Hopkins APL Technical Digest, vol. 34, no. 3, Oct 2018, pp. 374 -387.

[7] P. Voosen, "NASA will fly a billion-dollar quadcopter to Titan, Saturn's methane-rich moon", Science Mag., Jun 27th, 2019. https://www.sciencemag.org/news/2019/06/nasa-will-fly-billion-dollar-quadcopter-titan-saturn-s-methane-rich-moon

[8] Sony Energy Devices Corporation, "Lithium Rechargeable Battery," Technical Information, Jun 29th, 2012. https://www.powerstream.com/p/us18650vtc5-vtc5.pdf

[9] F. Affortunato, " Ingenuity – Specs and technology of the Martian drone," Technical Information, Apr 28th, 2021. https://4mydrone.com/en/blog-articles/ingenuity-spes-and-technology-of-the-martian-drone/

[10] NASA, "Six things to know about NASA's Ingenuity Mars helicopter," Technical Note, Apr 5, 2021. https://www.nasa.gov/feature/jpl/6-things-to-know-about-nasas-ingenuity-mars-helicopter

[11] J. D. Anderson, "Fundamentals of aerodynamics," Tata McGraw-Hill Education, 2010.

[12] A. Oyama, and K. Fujii, "Airfoil design optimization for airplane for mars exploration," In J-55, The Third China-Japan-Korea Joint Symposium on Optimization of Structual and Mechanical Systems, CJK-OSM3, Kanazawa, Ishikawa, 2004.

[13] The Guardian, "Nasa's Dragonfly mission to Saturn's Titan moon delayed,", Oct 1st, 2020. https://www.theguardian.com/science/2020/oct/01/nasas-dragonfly-mission-to-saturns-titan-moon-delayed-covid-life-earth

[14] L. W. Traub, "Range and endurance estimates for battery-powered aircraft," Journal of Aircraft, vol. 48, no. 2, Mar 2011, pp.703-707.