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REVIEW

Design and optimization of ion propulsion drone

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Electric propulsion technology is widely used in many kinds of vehicles in recent years, and aircrafts are no exception. Technically, UAVs are electrically propelled but tend to produce a significant amount of noise and vibrations. Ion propulsion technology for drones is a potential solution to this problem. Ion propulsion technology is proven to be feasible in the earth's atmosphere. The study presented in this article shows the design of EHD thrusters and power supply for ion propulsion drones along with performance optimization of high-voltage power supply for endurance in earth's atmosphere.

Keywords: ion propulsion, electroaerodynamics (EAD), electrohydrodynamics (EHD), eVTOL, UAV, drone

1. Introduction

Ion is proven to be the best propulsion system for spacecraft and satellites because of its high specific impulse, high efficiency, and silent propulsion in space. Despite this, researchers were finding this technology inadequate to be used in the earth's atmosphere earlier (1). Corona discharge is an efficient way of generating a strong electromagnetic field (EMF) between a positive and a negative electrode. The EMF generates high-velocity ions that transfer kinetic energy to nitrogen atoms available in the air; these nitrogen atoms collide with neutral air molecules and then race toward the negative electrode, which creates electrohydrodynamic flow prevalently known as ionic wind (2).

Figure 1 shows the ionic wind generation in earth's atmosphere. Here, a thin wire is used as an emitter carrying more than 20 kV positive charge and an airfoil with 20 kV negative charge. Ionization is the region where nitrogen atoms available in the air get charged and then it moves toward the plasma region where the collision of charged nitrogen atoms and neutral air molecules takes place resulting in momentum transfer. Essentially, these accelerated molecules race toward the negative-charged collector, which creates thrust known as ion thrust.

2. Literature review

MIT engineers built the very first ion-drive aircraft in 2018, which had no moving parts and was propelled by ionic wind. The design proposed in this study was an aerodynamic glider weighing around 2.3 kg. The ion thruster in this model was a 5 m wing with arrays of emitters and collectors. The emitter was a thin wire, and the collector was a metal foil supported by airfoils. The fuselage of the drone had provision for power supply and avionics equipment (3). The proposed design of an ion-drive aircraft by MIT is depicted in **Figure 2**.

A product called "Silent Ventus" is being developed by a tech company based in Texas called Undefined Technologies. The proposed model has manifested optimistic performance with an almost five-minute flight time. Furthermore, they have promised that they will increase flight time and reduce noise levels to as low as 70 dB in the coming years (4). The product being developed by Undefined Technologies is shown in **Figure 3**.

Design of an ion plasma jet thruster prototype that utilizes ion plasma generated by ion microwave is presented by Dan Ye et al. (5). This jet-ion thruster uses a high-voltage power supply and air to produce high-pressure flow. The aim of the research is to replace the traditional fossil-fueled jet engines

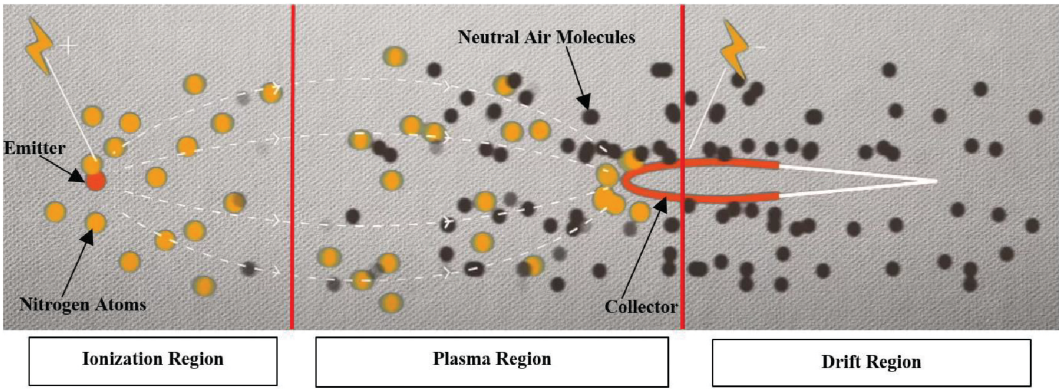

FIGURE 1 | In-atmosphere ion propulsion (3).

with jet-ion engines with no carbon emissions for potential use in the earth's atmosphere. The design of the jet-ion thruster is shown in **Figure 4**.

Figure 4 shows a design of magnetron, an igniter, a quartz tube, a circulator, and a compressed waveguide. Essentially, the magnetron is the heat wave source; absorption of reflected heat waves is done by the circulator. The compressed waveguide is used to increase the electromagnetic field (EMF). An ignition system is used in ion combustion chamber to generate ion plasma jet.

An air-breathing ion plasma thruster for lower Earth orbit maneuverability was designed by F. Romano et al. (6). The objective of the research was to replace the onboard propellant storage system with atmospheric nitrogen as a propellant. The schematic setup of the air-breathing plasma thruster is shown in **Figure 5**.

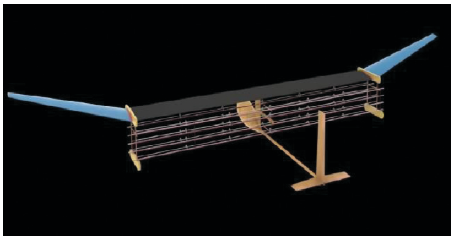

FIGURE 2 | Ion-drive aircraft by MIT (3).

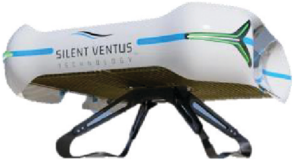

FIGURE 3 | Silent ventus by undefined technologies (4).

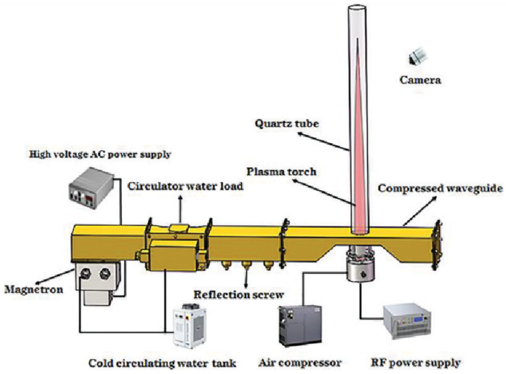

FIGURE 4 | Ion plasma jet thruster (5).

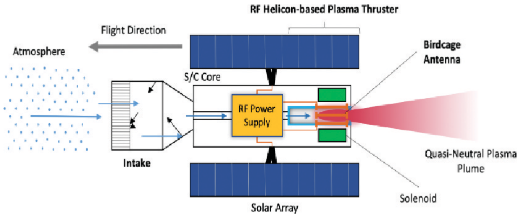

FIGURE 5 | Air-breathing plasma thruster (6).

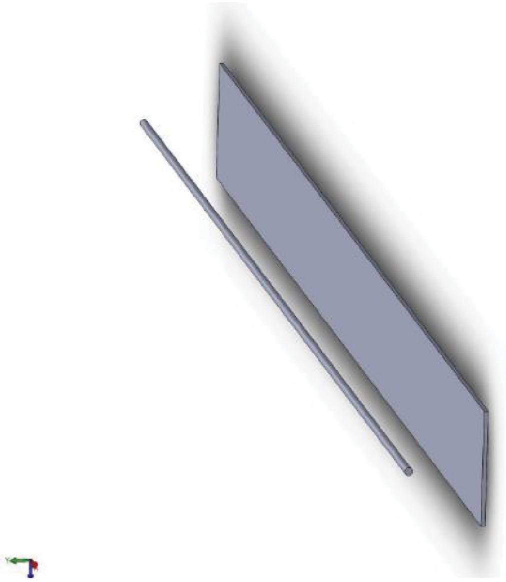

FIGURE 6 | Design of EHD thruster (7).

3. Design of the drone

This section includes the design of essential systems required for ion propulsion drone.

(1) Design of EHD thruster

Electrohydrodynamics thruster is the power plant of the drone. EHD thruster is made of two major components that are anode and cathode, commonly known as emitter and collector. The emitter is always charged with a high-voltage positive 40 kV DC supply and the collector is charged with a high-voltage negative 40 kV DC supply. **Figure 6** shows the design of EHD thruster.

The current-voltage relationship during the ion propulsion is derived by Townsend,

$$I = kV(V - V0)\ldots \tag{1}$$

where V and I are the voltage and current, respectively, k is the constant, and $V0$ is the onset voltage during the propulsion.

The power generated during the propulsion can be calculated as follows:

$$P = VI\ldots \tag{2}$$

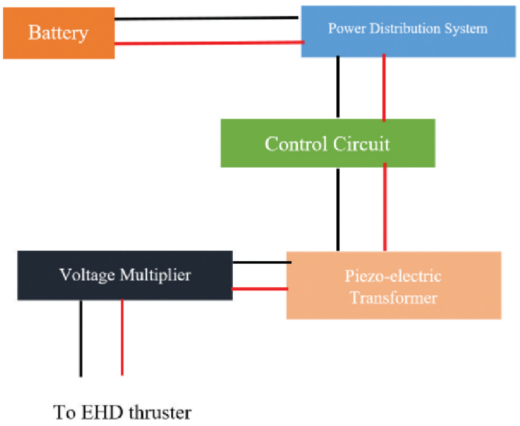

FIGURE 7 | Configuration of HV power supply (7).

TABLE 1 | Material properties.

Property	Copper	Aluminum	Glass epoxy
Thermal conductivity ($Wm^{-1}K^{-1}$)	400	235	
Young's modulus (GPa)	115	70	3.5
Poisson's ratio	0.34	0.35	0.4
Tensile strength (MPa)	210	80	275
Specific heat (kJ/kg K)	0.39	0.0009	
Thickness (mm)	1	0.016	1
Melting point (°C)	1085	660	
Boiling point (°C)	2562	2467	
Density (g/cm^3)	8.96	2.7	1.7

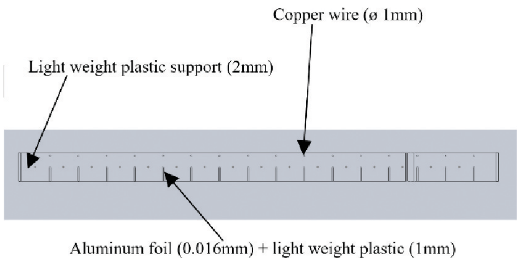

FIGURE 8 | Cross-section layout of EHD thruster.

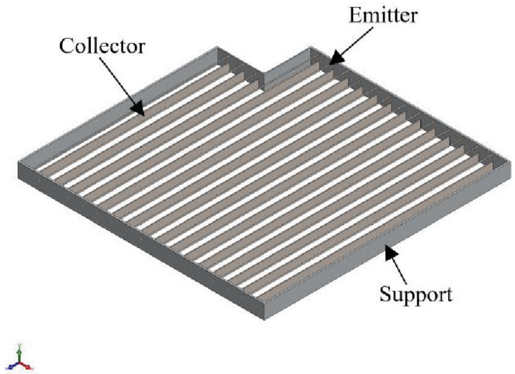

FIGURE 9 | Structural layout of EHD thruster (Isometric view).

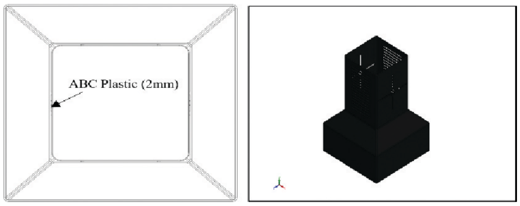

FIGURE 10 | Power supply and avionics equipment storage system.

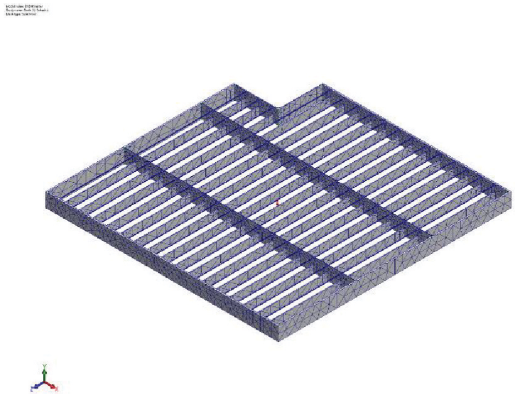

FIGURE 11 | Finite element model of EHD thruster.

The thrust generated during ion propulsion is derived using equation 3.1 and Mott-Gurney's law.

$$T = \int \rho E dV = \int \rho E A dx = \int \frac{JAdx}{\mu} = \frac{Id}{\mu} = \frac{kV\,(V - V0)}{\mu}\ldots \tag{3}$$

where thrust is T, and charge density is ρ, E is electric field, and μ and d denote ion mobility and distance between emitter and collector, respectively.

Hence, the thrust efficiency can be calculated as follows:

$$\frac{T}{P} = \frac{Id}{\mu VI} = \frac{d}{\mu V}\ldots \tag{4}$$

where P is the consumption of power due to ionization (7).

(2) Design of power supply

To power the EHD thruster and make it fly, it is essential to design a miniaturized high-voltage power supply, which is sustainable and capable of delivering 40 kV DC supply. The configuration of the high-voltage power supply is shown in **Figure 7**.

The power supply consists of a Li-Po battery, control circuit, piezo-electric transformer, and a voltage multiplier.

TABLE 2 | Electrohydrodynamics thruster static analysis results.

Load condition	Max. von Mises stress (MPa)	Max. strain	Max. displacement (mm)
Gravity load	1.684e−01	6.038e−05	5.161e−02

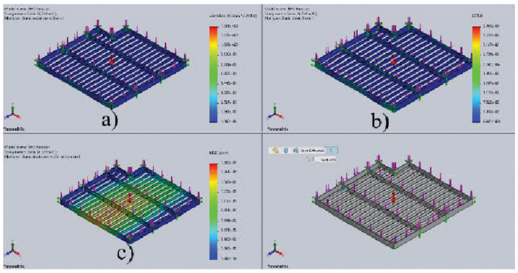

FIGURE 12 | (a) Stress, **(b)** strain, and **(c)** displacement indices for EHD thruster.

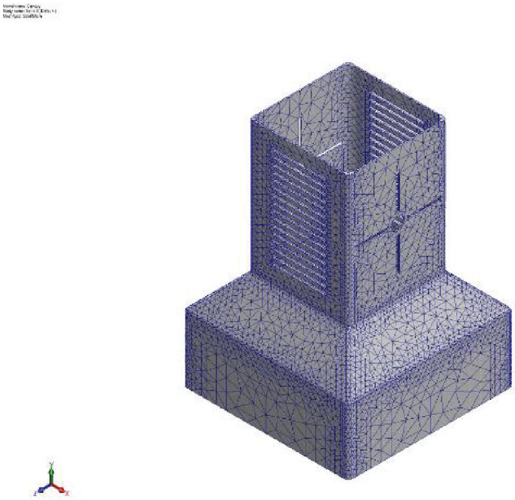

FIGURE 13 | Finite element model of power supply and avionics equipment storage system.

(a) Battery

While selecting the battery, the power-to-weight ratio is really important. Li-Po batteries are considered ideal for drones because of their high power-to-weight ratio (8).

(b) Piezo-electric transformer

Transformers are well known for their high electromagnetic fields (EMF) that tend to create disturbance. Hence, it is essential to use a transformer that induces negligible EMF. Piezo-electric transformers get precedence over other transformers (9).

(c) Voltage multiplier

To deliver high voltage, a voltage multiplier is essential that bears minimum weight. Dickson charge pumps typically deliver high-power from low-power sources of up to a few kilovolts (10).

(3) Structural design of airframe

The structure should be able to bear the weight of thrusters and power supply; hence, rigidity is one of the main parameters.

The main constraint for the design is the overall weight of the system. To make the lightweight structure (11), the structure of an EHD thruster can be made with lightweight composites. The materials that could be used for product development are given in **Table 1**. The provision for avionics and battery equipment can be made with lightweight and rigid plastic.

(a) EHD thruster

The structure of the EHD system is shown in **Figure 8**. The structure of the EHD thruster is designed to generate enough thrust to lift the drone.

As shown in **Figure 8**, the EHD thruster is made of epoxy, aluminum, and copper. The support and strips in between the supports are made of glass epoxy, and aluminum foil is placed on those strips, with a 1-mm diameter copper wire placed 1 cm above the aluminum foil. The 3D depiction of the EHD structure is shown in **Figure 9**.

TABLE 3 | Static analysis results for PSAE storage system.

Load condition	Max. von Mises stress (MPa)	Max. strain	Max. Displacement (mm)
Gravity Load	5.888e−03	2.263e−06	5.109e−04

TABLE 4 | Experimental thrust.

Voltage (kV)	Current (amp)	Thrust (N)
10	0.5	0.015
20	0.5	0.023
25	0.5	0.031
30	1	0.047
40	1	0.087

(b) Design of power supply and avionic equipment storage system

The storage system for power supply and avionics equipment is designed in such a way that it could also be used as landing gear because of the wide base of the storage system. The component would entirely be made of ABC plastic in order to increase the strength and reduce the weight. The design of the storage system for power supply and avionics equipment is shown in **Figure 10**.

When the aircraft is landing, a significant amount of impact must be absorbed by the base as well as the landing gear. Hence, a base should have characteristics like a high capacity for elastic strain energy, high strength, medium stiffness, and lightweight (11). While landing the aircraft, the base would undergo large deformation, hence the thickness of the lower part of the storage system is more. The base is designed with the consideration of weight of 2 kg and a minimum vertical velocity of approximately 1.5 m/s.

(4) Structural analysis of airframe

(a) EHD thruster

The EHD thruster consists of aluminum foil, copper wire, and epoxy sheets. The initial step in FEA (finite element analysis) is to construct the geometry. The geometry of EHD thruster is generated by the computer-aided program called solidworks and simulated in solidworks simulation. Furthermore, a grid was created for FEA analysis using the design. The FEA model of the EHD thruster is depicted in **Figure 11**.

A static structure analysis was carried out. A von Mises criterion was used in order to evaluate the stress failure in the structure (12). Two load conditions were applied for the analysis that are shown in **Table 2**; it also includes analysis results for the given load conditions.

The analysis showed that the structure was able to sustain the load under the given load conditions. The analysis index for EHD thruster is shown in **Figure 12**.

(b) Power supply and avionics equipment (PSAE) storage system

The Solidworks software was used for static analysis of the PSAE storage system. The geometry was used for FEA analysis under a gravity load. The FEA model for the PSAE system is shown in **Figure 13**.

Table 3 shows the static analysis results for the PSAE storage system.

4. Performance optimization of high-voltage power supply

(a) Frequency variation

The system demands a high voltage from the power supply; the output voltage in PZT varies with frequency of current (13). According to the experimental analysis, PZT works best when the resonance frequency is in between 45 and 46 kHz.

(b) Variation in duty cycle

The output voltage is dependent on the driving signal and its duty cycle (14). When the duty cycle is 50%, the power supply delivers the highest output voltage. The output voltage can be regulated by successfully tuning the duty cycle. The voltage determines the thrust to be generated by the EHD system. Hence, throttle and yaw can be controlled by successful tuning of the duty cycle signal.

(c) PID tuning of HV power supply

To enable navigation and reliable performance of the drone, it is essential to tune the autopilot with the power supply. The most essential configuration is pitch and roll because it contributes to effective navigation and stable flight (15).

After successful PID tuning of the HV power supply, we would be able to achieve navigation and control for the drone. The throttle of the drone can be controlled by regulating the power supply. The complete navigation of the drone can be achieved by thorough tuning of roll, pitch, and yaw (16).

5. The ion propulsion drone

The conceptual design of the drone is shown in **Figure 14**. The dimensions and overall estimated weight of the drone are 70 cm × 70 cm and 2.5 kg, respectively. The configuration of the drone is quite identical to a quadcopter, but the motors are replaced by EHD thrusters. The changes can be made to the design in order to improve its sustainability in the environment. Unlike the multirotor, this drone will have voltage regulators instead of electronic speed controllers (ESC), which will give the desired voltage to EHD thrusters as per the input given.

To give desired inputs to the EHD thrusters, the tuning of thrusters with autopilot is the key (17). The thrust of EHD systems can be controlled by giving appropriate PWM (pulse width modulation) inputs from the autopilot to the voltage regulator.

5.1. Mathematical model

The efficiency of the EHD thruster solely depends on the amount of thrust produced by the EHD thruster. In order to make the mathematical model, we need to make some assumptions, which are listed below, in order to analyze thrust created by the EHD thruster.

(a) The earth's atmosphere has an abundance of N_2, and its atomic number is 7; hence, nitrogen is the ideal fuel for the EHD thruster.

(b) The acceleration of ionized molecules is independent of the collision of other molecules.

(c) The thrust generated by EHD thrusters is a function of transfer of momentum caused by repulsion between emitter and collector.

$$T = \frac{dp}{dt} \tag{5}$$

The momentum that takes place due to repulsion between emitter and collector is a function of kinetic energy (J), which yields the potential difference between emitter and collector, which is assumed to be 40 keV in this case:

$$J = \frac{m}{2v^2} \tag{6}$$

$$v^2 = \frac{2J}{m} \tag{7}$$

Here, we need to calculate the mass of N_2

$$mass\ of\ N_2 = 2 \times atomic\ mass\ of\ N_2 \times \frac{E}{c^2}$$

$$= \frac{(2 \times 14.0067 \times 931 \times 10^6)}{(3 \times 10^8)^2}$$

$$v = 2.9 \times 10^{-7}\ kg \approx 4.65 \times 10^{-26} amu$$

$$\therefore v = \sqrt{\frac{2 \times 40000}{2.9 \times 10^{-7}}}$$

$$v = 5.25 \times 10^5$$

By Newton's second law, we can get a certain number of ions flowing per second due to ionization. The value of 1C at 1A current flowing per second is 6.241×10^{18}.

Hence, from equation 5.1,

$$T = mass\ of\ N_2 \times flow\ velocity \times current \times charge$$

$$= 4.65 \times 10^{-26} \times 5.25 \times 10^5 \times 1 \times 6.241 \times 10^{18}$$

$$= 0.152\ N$$

The thrust created by the ionic thruster would be 0.152 N. An increase in current will result in thrust augmentation, which means the current applied is directly proportional to the thrust.

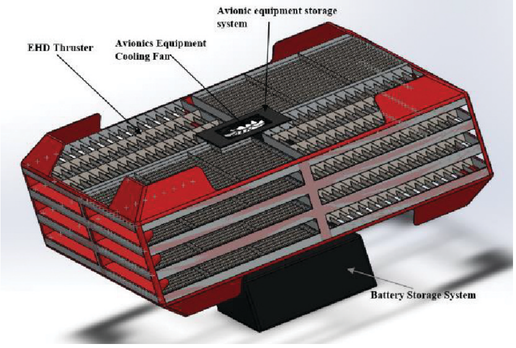

FIGURE 14 | Conceptual design of ion propulsion drone.

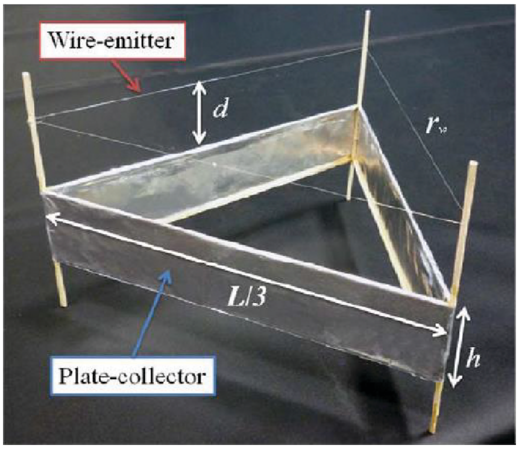

FIGURE 15 | Experimental setup.

5.2. Experimental setup

A single-stage ion thruster was designed in order to get the experimental results. The experimental setup is shown in Figure 15. A high-voltage DC supply was provided to the circuit in order to achieve a potential difference of 10–40 kV between the electrodes. To calculate the thrust, we used the formula $T = A_m a^2$, where A is the air mass flowing through area a.

The experimental results are given in Table 4. By experimental analysis, we can see that increase in voltage and current results in an increment in thrust.

6. Conclusion

Ion propulsion technology has a lot of potential for use in UAVs in the coming years. The project being developed by Undefined Technologies shows its robustness in the atmosphere. The complete design of the EHD system and power supply, along with the airframe design, is thoroughly presented in this article. The performance optimization of high-voltage power supply and its PID tuning are essential for the navigation and endurance of the drone in the atmosphere, which is the subject of this article. Despite the fact that this article presents a theoretical and an experimental analysis of the EHD thruster, it provides a clear view of ion propulsion in the atmosphere.

References

1. NASA. *NASA-Ion propulsion*. (2016). Available online at: https://www.nasa.gov/centers/glenn/about/fs21grc.html (accessed on 07 Jan, 2023).
2. Guan Y, Vaddi RS, Aliseda A, Novosselov I. Analytical model of electro-hydrodynamic flow in corona discharge. *Phys Plasmas.* (2018) 25:083507. doi: 10.1063/1.5029403
3. Chu J. *MIT Engineers fly first-ever plane with no moving parts*. (2018). Available online at: https://news.mit.edu/2018/first-ionic-wind-plane-no-moving-parts-1121 (acessed on 09 Jan, 2023).
4. Undefined Technologies. *Next generation silent drone*. (2023). Available online at: https://www.undefinedtechnologies.com/ (accessed on 12 Jan, 2023).
5. Ye D, Li J, Tang J. Jet propulsion by microwave air plasma in the atmosphere Jet propulsion by microwave air plasma in the atmosphere. *AIP Adv.* (2020) 10:055002. doi: 10.1063/5.0005814
6. Romano F, Herdrich G, Crisp NH, Edmondson S, Haigh S, Oiko VTA, et al. Design of an intake and a thruster for an atmosphere-breathing electric propulsion system. *CEAS Space J.* (2022) 14:707–15.
7. Rushikesh P. Design of power supply and EHD system for ion-propulsion drone. (2022) 1:35–8. doi: 10.54646/bije.007
8. Nagel L. *A Guide to lithium polymer batteries for drones*. (2021). Available online at: https://www.tytorobotics.com/blogs/articles/a-guide-to-lithium-polymer-batteries-for-drones (accessed on 15 Jan, 2023).
9. Vazquez Carazo A. Piezoelectric transformers: an historical review. *Actuators.* (2016) 5:12. doi: 10.3390/act5020012
10. Park S, Yang J, Rivas-Davila J. A hybrid cockcroft-walton/dickson multiplier for high voltage generation. *IEEE Trans Power Electron.* (2020) 35:2714–23. doi: 10.1109/TPEL.2019.2929167
11. Park Y, Nguyen K, Kweon J, Choi J. Structural analysis of a composite target-drone. *Int J Aeronaut Space Sci.* (2011) 12:84–91. doi: 10.5139/IJASS.2011.12.1.84
12. Groh R. A Tailored Nonlinear Slat-Cove Filler for Airframe Noise Reduction. *Conference on smart materials, adaptive structures and intelligent systems SMASIS2018.* San Antonio, TX: American Society of Mechanical Engineers (2018). doi: 10.1115/SMASIS2018-8079
13. Tempo Automation. *Using piezoelectric transformers in power electronics systems*. (2023). Available online at: https://www.tempoautomation.com/blog/using-piezoelectric-transformers-in-power-electronics-systems/ (accessed on 01 Jan, 2023).
14. Vlsi Universe. *Duty cycle variation of inter-clock timing paths*. (2023). Available online at: https://vlsiuniverse.blogspot.com/2017/10/duty-cycle-variation.html#:~{}:text=Duty%20cycle%20variation%20is%20always,certain%20fixed%20point%20of%20time (accessed on 04 Jan, 2023).
15. Ardupilo. *Pitch and yaw controller tuning*. (2023). Available online at: https://ardupilot.org/plane/docs/roll-pitch-controller-tuning.html (accessed on 05 Jan, 2023).
16. Rice RC. *PID tuning guide*. (2010). Available online at: https://docs.px4.io/main/en/config_mc/pid_tuning_guide_multicopter.html (accessed on 09 Feb, 2023).
17. Ardupilot. *Advanced tuning*. (2022). Available online at: https://ardupilot.org/copter/docs/tuning.html (accessed on 13 Feb, 2023).
18. Poon HS, Lam MKK, Chow M, Li WJ. Noiseless and vibration-free ionic propulsion technology for indoor surveillance blimps. *2009 Proceedings - IEEE international conference on robotics and automation*. Kobe: IEEE (2009). p. 2891–6. doi: 10.1109/ROBOT.2009.5152843
19. Parekh J. *The thrust generated by DIY ion thruster*. *Int J Adv Res Ideas Innov Technol.* (2020) 6:1064–8.