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Noiseless and Vibration-Free Ionic Propulsion Technology for Indoor Surveillance Blimps

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***Abstract*—We present in this paper a novel indoor blimp that is propelled by a propulsion technology that uses no moving mechanical parts and thus is noiseless and vibration free. In our prior work reported at IEEE/ASME AIM 2007, we demonstrated several prototype propulsive units (with asymmetric capacitor configurations) that lift themselves into air. Using these basic propulsive units ("Ionic Flyers"), we have recently developed an indoor flying blimp that has a propulsion system with no moving mechanical parts and thus generates no noise or vibration -- the Ionic Propulsion Blimp. The key to successfully create this novel indoor flying system is the development of a power generation system that includes an 11.1V battery which is capable of generating ~20kV DC voltage continuously over time for a load in the MΩ range. The architecture of this ionic power system will be presented. A detailed parametric analysis and an optimal design methodology of the Ionic Flyer are also discussed. Initial experimental results of the Ionic Propulsion Blimp are also summarized in this paper.**

Keywords: Ionic Flyer, Ionic propulsion, indoor blimp

I. INTRODUCTION

NOWADAYS, miniaturized helicopters and planes embedded with sensing and control systems are widely used for indoor and outdoor surveillance missions. These flying systems use conventional aerodynamic principles to produce lift and thrust – which has already been researched and understood for many decades. However, they require powerful rotating/moving mechanical parts in order to generate strong aerodynamic flow for lift and propulsion. Thus, these flying systems generate significant noise during operation and may also unintentionally damage surrounding objects due to their rotating blades or propeller. As for surveillance missions, mechanical vibrations generated by moving parts such as the rotating rotors, blades, propellers make them unstable in terms of capturing pictures or videos in real-time.

In this paper, we will present our group's undergoing development of a novel ionic propulsion technology that generates propulsive force without using moving parts and generates no noise. Moreover, we will show that this propulsive technology is scalable. By increasing the physical dimensions of a basic 'propulsive unit', i.e., the size or designs of an "Ionic Flyer" appropriately, the propulsive force could be increased accordingly. To demonstrate the potential application of this indoor ionic propulsion technology, an "Ionic Propulsion Blimp" is currently under development in our laboratory. It uses a helium blimp to balance the weight of the whole system and uses an Ionic Flyer to provide propulsion force. The Ionic Flyer does not require any mechanical moving part and only use high voltage (usually higher than 10kV) to produce thrust. It converts electrical energy directly to mechanical energy for propulsion, and therefore, it does not contain any dangerous rotating/moving components which generate unwanted noise and vibration [1]. As a result, the Ionic Propulsion Blimp can operate silently and stably which will eventually benefit indoor surveillance applications.

Fig. 1 shows the basic structure of the Ionic Flyer with wire-plate electrode configuration (other configurations were discussed in [1]). The parameters L, h, d, and r_w represent the perimeter length, the collector height, the separation distance between electrodes and the radius of the emitter wire respectively.

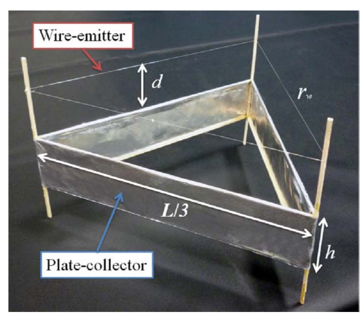

Fig. 1. The structure of Ionic Flyer with wire-plate electrode configuration.

The Ionic Flyer is basically an asymmetrical capacitor which uses air as the dielectric material. It contains two primary elements – an emitter and a collector. The emitter is usually a thin wire which is connected to high voltage source, whereas the collector is typically a plate foil which is connected to ground.

By applying a high voltage between two asymmetric electrodes, electric corona discharge will occur [2]. A high electric field near the wire-emitter causes the surrounding air molecules to become ionized which partially breaks down to produce a high density of ions. As a result, the charged ions are drifted towards the grounded plate-collector and this causes an electric current flow between the electrodes. During the movement of ions, high frequency collisions with neutral air molecules occurred. Momentum is transferred from the ionized gas to the neutral air molecules, resulting in movement of gas towards the collector. Therefore, thrust is generated by the Ionic Flyer from plate-collector to the wire-emitter. If the input power is high enough, the output force will balance its own-weight and therefore the Ionic Flyer can be lifted up.

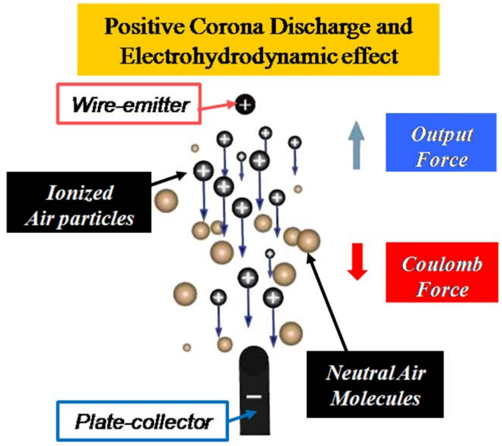

Fig. 2. Illustration of the basic operational theory of the "Ionic Flyer"[1].

Since the Ionic Flyers needs a large high voltage (kV range) power supply to produce lift, it is impossible to make the Ionic Flyer to be an autonomous flying device due to the weight of the existing kV generation systems. On the other hand, the force generated by Ionic Flyer is relatively weak compared to those using conventional aerodynamic principles. Therefore, the critical issues to be solved in order to make Ionic Flyer into an autonomous flying machine are 1) optimization of the design for the Ionic Flyers to produce lift force, and 2) miniaturization, weight reduction, and increased efficiency of a kV-range of high voltage (HV) power supply. Essentially, an analysis is required to understand the input-power to lift-generation efficiency of the Ionic Flyer based on the state-of-the-art HV power generation technology.

II. Parametric Models of the Ionic Flyer

Based on the lifting phenomenon of Ionic Flyer, Chung and Li performed systematic experimental analyses on Ionic Flyers with wire-plate electrode configuration and introduced parametric models which are critical to the understanding of the operational principles of the Ionic Flyers [1].

The effects of all primitive parameters that affect the performance of the Ionic Flyers have also been discussed by Chung in [3]. The Current-Voltage model for Ionic Flyers with wire-plate configuration is derived as

$$I = C(L,d)(V - V_0(r_w, d))^2 \quad (1)$$

where I is the input current in mA, V is the input voltage in kV, C is the current gain which is written as

$$C(L,d) = K_e \cdot \frac{L}{d^2} \quad (2)$$

where K_e is the electrical environmental constant in mA/mm·kV^2 which reflects the changes of the environmental conditions. V_0 is the onset voltage which is calculated by the modified Peek's equation and described as

$$V_0(r_w, d) = G(r_w) m_0 g_0 \delta \left(1 + \frac{0.0301}{\sqrt{\delta \cdot r_w}}\right) r_w \cdot \ln\left(\frac{d}{r_w}\right) \quad (3)$$

where m_0 is irregularity of the wire, δ is the air density factor, g_0 is the breakdown field strength, and G is the derived modification factor with equation of

$$G(r_w) = 1 + e^{-\left(\frac{r_w}{4\times10^{-5}}\right)}. \quad (4)$$

According to (1), it is shown the current and voltage is in quadric relationship. While the force-voltage are in linear relationship and formulated as

$$F = J(L,d)(V - V_f(V_0)) \quad (5)$$

where F is the generated force in gram, V is the input voltage in kV, J is the force gain which is written as

$$J(L,d) = K_f \cdot \frac{L}{d^{0.54}} \quad (6)$$

where K_f is the lift-force environmental constant in g/mm$^{0.46}$·kV^2 which depends on the environmental conditions. V_f is the barrier voltage which represents the minimum input voltage for the Ionic Flyer to create force. It is related to the maximum power loss before the Ionic Flyers is able to generate lift-force and this power loss P_c is called Initial Power Dissipation (IPD). It is found to be proportional to the perimeter length L of Ionic Flyer and defined as

$$P_c = K_p \cdot L \quad (7)$$

where K_p is the IPD constant which represents the maximum power loss per unit length in the process of corona discharge. By substituting V_f into (1) and P = IV, the IPD can also be derived and V_f can be determined by

$$P_c = CV_f (V_f - V_0)^2 = K_p \cdot L \quad (8)$$

Finally, using the above equations, a third-order equation for the Lift-force to Power Relationship is described by

$$P = C\left(J^{-1}F + V_f(V_0)\right)\left(J^{-1}F + V_f(V_0) - V_0\right)^2 \quad (9)$$

where P is the input power in Watt, F is the output force in gram, and J^{1} is the reciprocal of the force gain J (refers to (6)).

Using the Current-Voltage model, the Force-Voltage model, and the Force-Power model, the performance of the Ionic Flyer with fixed structure under specified voltage can be calculated. In other words, the structural design of the Ionic Flyer can be optimized by finding the maximum Force-to-Power ratio which is derived from (1) and (5), as

$$\frac{F}{P} = K_{f/e} d^{1.46} \frac{(V - V_f(V_0))}{V(V - V_0)^2} \quad (10)$$

where $K_{f/e}$ is the environmental constant, equal to K_f / K_e.

Using the above equations, based on engineering requirements, Ionic Flyers with optimal force/power ratio can be obtained. Fig. 3 shows the parametric plot of (10) using empirical data collected by Chung and Li [1]. The

Ionic Flyers used to propel the Ionic Propulsion Blimp described in this paper were built using the design data from Fig 3.

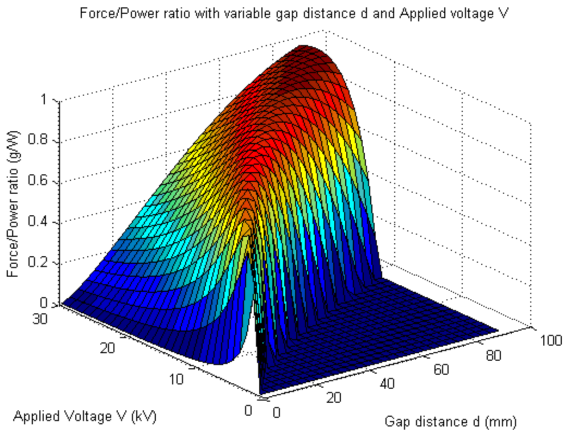

Fig. 3. Variation of Force-to-Power ratio with gap distance and applied voltage. ($K_e = 0.001755\text{mA/mm}\cdot\text{kV}^2$, $K_f = 0.005238\ \text{g/mm}^{0.46}\cdot\text{kV}^2$).

III. Design of High Voltage Power Supply

In order to make the Ionic Flyer into an autonomous flying system, a small High Voltage power supply, which only weighs 80g, was developed. The power supply is capable of supplying DC high voltage of ~20kV under a wide range of load in MΩ range from a single battery (~11.1V).

Fig. 4 illustrates the basic configuration of the power supply which is composed of 1) Battery, 2) Step-up transformer, 3) Voltage multiplier, and 4) Control circuit.

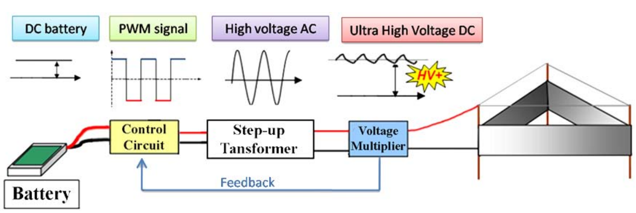

Fig. 4. The basic configuration of the high voltage power supply.

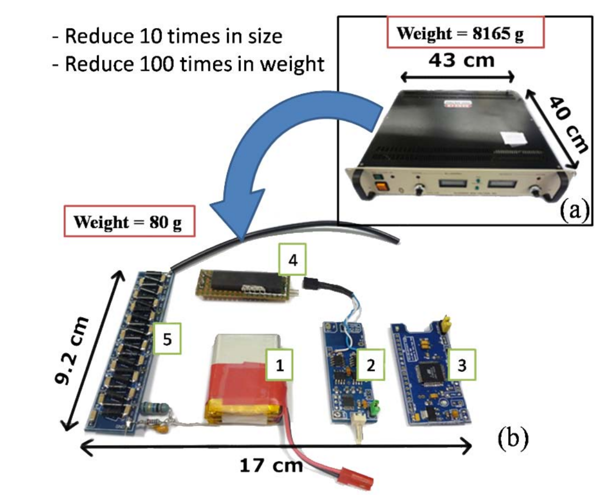

Fig. 5. (a) A conventional HV Power Supply which is usually used to operate Ionic Flyer as described in [7] and [8]. (b) The new battery-driven HV Power-Supply developed by our group (1: Battery, 2: Control circuit, 3: Microprocessor + Bluetooth, 4: Piezo Transformer, 5: Voltage Multiplier).

A. Battery

A single battery is used as the power source to the entire HV power supply, and therefore it should have a high energy density. By comparing the six most commonly used rechargeable battery, Lithium-ion Polymer (Li-Poly) battery has the best Weight-to-Energy ratio (≈ 6.1g/W·h) among the other batteries [4]. The weight of battery can be calculated by

$$W_b = R_b \times P \times t \qquad (11)$$

where R_b is weight-to-energy ratio of the battery in g/W·h (≈ 6.1g/W·h for Li-Polymer), P is the output power in Watt, and t is the operation time required in hour. A 450mAh 3-cell Li-Poly battery is used in the prototype which gives around 11.1V@1.2A to the HV power system for about 20 minutes.

B. Step-up transformer

The step-up transformer can generate high voltage AC output from a relatively low voltage. Conventionally, high frequency coil transformer is used; however, those electro-magnetic transformers will generate high electro-magnetic interference (EMI) which affects the wireless control and sensing system. The main disadvantage of the coil transformer is the heavy weight which diverges from the objective of miniaturizing both the weight and volume of the power system, i.e., the weight-to-power ratio of coil transformer is high compared to the piezoelectric ceramic transformer which is used in our HV power system [5].

Piezoelectric ceramic (PZT) transformer generates high voltage efficiently without any magnetic material, so it will only induce a very low EMI that does not affect the other components of the overall system. On the other hand, it is non-flammable and has an excellent weight-to-power ratio, usually less than 1g/W. The weight of the transformer can be found by

$$W_t = R_t \times P \qquad (12)$$

where R_t is weight-to-power ratio of the transformer in g/W (≈ 0.864g/W for our design), and P is output power required in Watt.

C. Voltage Multiplier

The output voltage of transformer is further amplified and rectified by the Cockcroft Walton (CW) voltage multiplier in order to drive the Ionic Flyer. The CW circuit is made up of a voltage multiplier ladder network of capacitors and diodes to generate high voltage. Using only capacitors and diodes, it can step up a relatively low voltage to extremely high value, while at the same time being far lighter and cheaper than a transformer. Besides, the voltage across each stage of the cascade is equal to twice of the peak input voltage, so feedback can be drawn from the first stage with potential divided in order to sense the output voltage of the power supply.

Usually, the capacitance of the HV capacitors in CW circuit is not the issue of concern when designing a HV power supply, i.e., the performance of the circuit does not depend on the capacitance [6]. However, it does affect the output when the capacitance is low and the current output is relatively large. Fig. 6 shows the performance of CW circuit using different capacitance for I_{out} = 0.5mA. It shows that the capacitance should be large enough in order to drive a higher current with a better performance. In our design, a silicone-sealed 10-stage CW circuit with 1000pF SMD HV capacitors is used for the HV power supply.

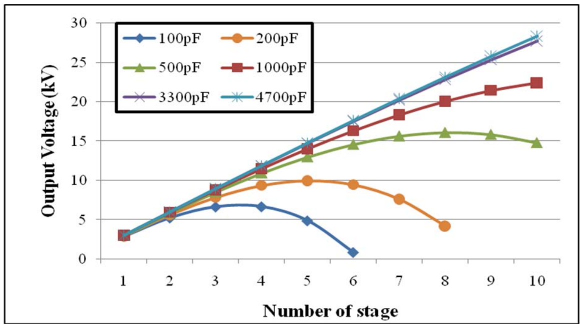

Fig. 6. Output of CW circuit under different capacitances (I_{out} = 0.5mA, V_{in} peak = 1.5kV, and frequency = 47kHz).

D. Control Circuit

The main objective of the control circuit is to convert DC voltage into pulsed DC voltage under specified frequency. To achieve this, an H-bridge switching algorithm is used. By sending the driving signal with small time delays, the input voltage will then be switched with specified frequency and input to the PZT. Fig. 7 describes how the current flow through the PZT with different driving signals.

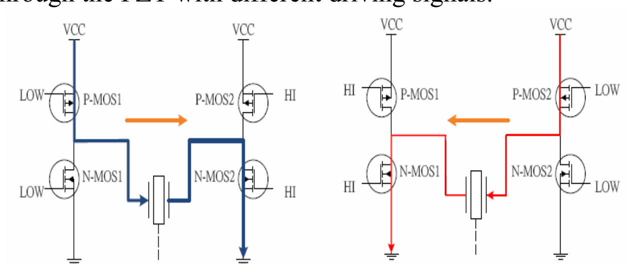

Fig. 7. Current flows through the PZT with different driving signal using Full H-Bridge driving algorithm.

PZT is required to drive under the resonance frequency in order to get the highest step-up voltage gain, but the resonance frequency will be shifted during operation due to temperature and environmental change. Therefore, a resonance frequency tracking system which compares the feedbacks from the voltage multiplier is built into the control circuit.

Initially, the driving frequency is set near the resonance frequency of the PZT. Once the controller enables the system, a high voltage will be generated and a feedback signal (Feedback0) will be received from the multiplier. After that, the controller will start changing the driving frequency in one direction (increase or decrease) and hence another feedback signal (Feedback1) will be received. By comparing magnitude of Feedback0 and Feedback1, the variation of output voltage due to the change of driving frequency can be known.

The controller keeps the changed of driving frequency when the output is increasing, i.e. Feedback1 is greater than Feedback0. Similarly, the driving frequency will be restored when the output is decreasing, i.e. Feedback1 is smaller or equal to Feedback0, and the driving frequency will be changed with opposite direction (increase or decrease) in the next iteration.

Using this algorithm, the driving frequency that gives maximum output, i.e. resonance frequency, can be reached in a short period of time. Also, it will be kept tracked during operation in order to achieve the highest performance for the HV power supply.

On the other hand, the control circuit also acts as a user control interface. It allows users to control the system wirelessly using Bluetooth Technology. Users can get the system information, enable the system and control the driving signal in order to control the output of the power supply.

IV. Performance of High Voltage Power Supply

A. Varying the Frequency

As the power supply generates high voltage with utilizing PZT, the output varies with the driving frequency. After a parametric experimental study, the PZT is shown to perform the best when resonance frequency (about 46 kHz) is reached.

B. Varying the Duty Cycle

The output voltage will also change with the duty cycle of the driving signal. Experimental analysis shows that the highest output voltage is achieved when duty cycle is 50%. Note that by tuning the duty cycle, the output voltage can be controlled. As the force generated by Ionic Flyer depends on the applied voltage, the force can also be controlled by tuning the duty cycle of driving signal.

C. Efficiency

During the step-up process, power is lost due to heat dissipation, corona discharge, or other environmental issues. Fig. 8 shows the efficiency of the power supply can be found by plotting out the power input versus output. For our HV power supply, the efficiency is about 36 %.

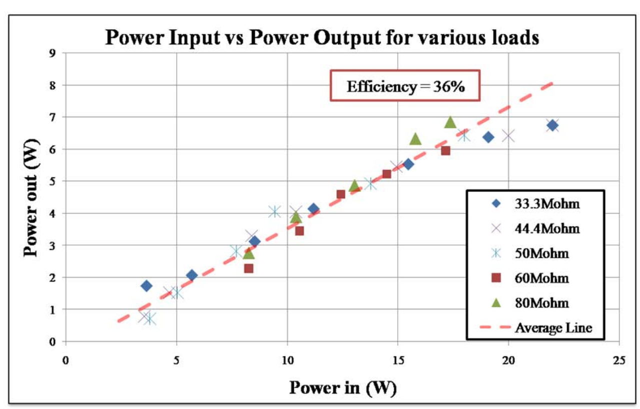

Fig. 8. Power input versus power output for various loads.

V. Possibility Analysis of On-board Power Supply

Many researchers or hobbyists aim to maximize the force generated by Ionic Flyers in order to lift them with a self-sufficient on-board power supply, but never succeeded. The possibility can be analyzed systematically by using the parametric models which were described in Section II.

Using force-voltage model (5), the force F generated by Ionic Flyer can be found. Assume W is the total weight of the HV power supply, the total net force F_{net} will be

$$F_{net} = F - W \tag{13}$$

If F_{net} is greater than zero, it means that there is a net lift force acting on the Ionic Flyer. In other words, the Ionic Flyer can be lift up with the on-board power supply. This can also be proved by finding the Net-Force-to-Power ratio (F_{net}/P) to be greater than zero, as the Power P is always a positive real number.

Without loss of generality, power loss is ignored and only the essential components of a portable power supply, i.e. the battery and the step-up transformer, are counted as the total weight of the power supply. Using (5), (11), (12) and (13), the Net-Force-to-Power ratio is derived as

$$\frac{F_{net}}{P} = \frac{J(V - V_f(V_0)) - R_b \times P \times t - R_w \times P}{P} \tag{14}$$

By $P=IV$ and after simplification, (14) becomes

$$\frac{F_{net}}{P} = K_{f/e} d^{1.46} \frac{(V - V_f(V_0))}{V(V - V_0)^2} - R_b \times t - R_w \tag{15}$$

where $K_{f/e}$ is the environmental constant, equal to K_f / K_e. (Please refer to Section II for details). From the equation, the Net-Force-to-Power ratio only depends on the gap distance d, applied voltage V and the operation time t. To analyze the possibility of on-board power supply, we just assumed a short time, says 5 minutes, as the operation time, and therefore the Net-Force-to-Power ratio with various gap distance d and applied voltage V can be calculated. Fig. 9 shows the minimum gap distance and applied voltage in order to make the Net-Force-to-Power ratio greater than zero.

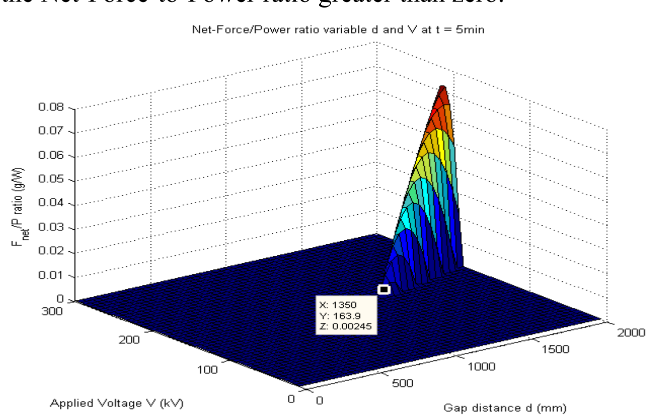

Fig. 9. Net-Force/Power ratio with variable gap distances and applied voltages for t = 5min (K_e = 0.001755mA/mm·kV^2, K_f = 0.005238 g/mm$^{0.46}$·kV^2, R_b=6.1 g/W·h, R_t=0.864 g/W).

According to Fig. 9, in order to lift the Ionic Flyer with its on-board power supply even for only 5 minutes, it is required to have 163.9kV as the applied voltage with 1.35m as the gap distance between the wire and the plate. Such a high voltage output is impossible to generate from a miniaturized HV power supply using the state-of-the-art technology (to the best of our knowledge after extensive Internet search). Besides, the Net-Force-to-Power ratio is only 0.00245 g/W when ignoring the actual weight and power loss. Hence, to the best of our knowledge and based on the parametric equations, we can conclude that it is infeasible for the Ionic Flyer to lift up with an on-broad power supply (i.e., battery, transformer and circuits) using only the force generated by Ionic Flyer. Therefore, the Ionic Propulsion Blimp is proposed and which is introduced in the next section to demonstrate a basic application of the Ionic Flyer.

VI. Ionic Propulsion Blimp

An Ionic Propulsion Blimp has been developed which can operate silently, stably, and does not contain any mechanical moving part. A helium blimp is used to generate auxiliary lift force to balance the weight of the HV power supply and the Ionic Flyer that acts as a thruster to generate propulsion force. In the near future, an advanced control and navigation system will also be developed and deployed on the Blimp.

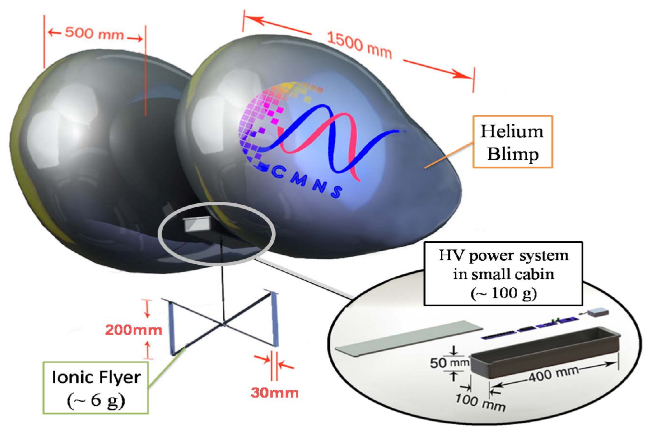

Fig. 10. Illustration of the basic components of the Ionic Propulsion Blimp.

A. *Required volume of the blimp*

Helium is a noble gas which is stable, non-flammable and lighter than air. The lifting force F_b of the helium blimp in gram can be calculated by

$$F_b = (\rho_{air} - \rho_{He}) \times Vol - \rho_{blimp} \times Vol \tag{16}$$

where ρ_{air} is the density of Air which is 1.29g/L, ρ_{He} the density of Helium which is 0.1786g/L, Vol is the volume of the blimp in L and ρ_{blimp} is the density of the blimp which is about 0.4g/L for Mylar balloon.

The total weight of the whole system is about 150g and the required volume of the blimp is found to be 211L (7ft^3) using (16). As a result, two 141.5L (5ft^3) balloons are used to balance the weight of the system and the extra payloads. Fig. 11 shows the prototype of the Ionic Propulsion Blimp which is used for the experimental results presented below.

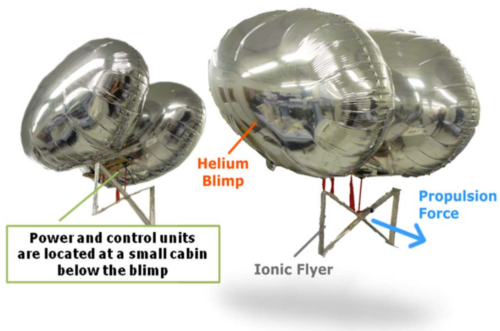

Fig. 11. Prototype of the Ionic Propulsion Blimp.

B. *Experimental results of the Ionic Propulsion Blimp*

The Ionic Propulsion Blimp was shown to operate successful and some flight tests were performed. The accompanying video with this paper shows three tests for the ionic propulsion system.

First is the lifting test of an optimally designed Ionic Flyer which can lift up stably using the HV power supply developed by our group. Two red papers are used to show the air flow generated by the Ionic Flyer.

Second experiment shows the Ionic Flyer in horizontal configuration which is the configuration that they are mounted on the blimp. The test performed shows how the Ionic Flyer operates in horizontal direction with various duty cycles of the driving frequency. A force gauge and an air flow meter are used to monitor the output of the Ionic Flyer. It shows that about 6g force with 0.7m/s air flow is generated with 50% duty cycle.

Finally, the Ionic Flyer with the entire power system is mounted on the blimp and a speed test is performed. The control circuit is connected wirelessly with a user's computer using Bluetooth, so that the user can control the operation of the Ionic Propulsion Blimp. After enabling the movement, the Blimp moves forward silently and stably using the thrust from the Ionic Flyer. The following sequential pictures show the movement of the Ionic Propulsion Blimp. Time taken for each 0.5m is recorded and which shows that the blimp is accelerated from 0.33m/s to 1.0m/s within 3.25s. Therefore, the forward acceleration is about $0.2 m/s^2$.

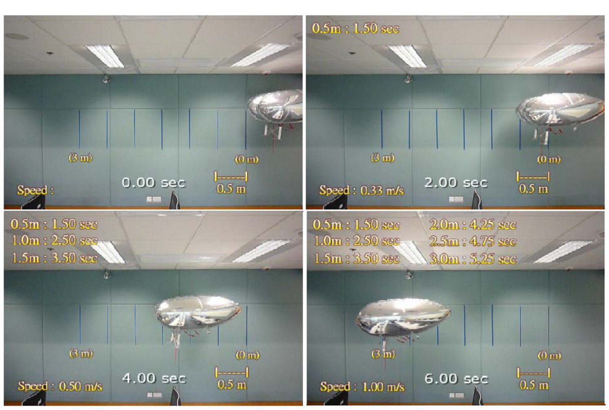

Fig. 12. Movement of Ionic Propulsion Blimp.

VII. Conclusion

This paper presents a design methodology for optimizing the force generated by the Ionic Flyer -- a novel thrust generation system that uses high voltage to give thrust without any mechanical moving parts. An extensive analysis was performed to understand the power-input to lift-force efficiency of the Ionic Flyer—which showed that it is not feasible to lift an individual Ionic Flyer by including its own on-broad power supply, given the state-of-the-art power generation technology. However, a light-weight, battery-driven, and miniaturized high voltage power supply was developed in order to allow the Ionic Flyer to be attachable and provide thrust to flying systems, e.g., a blimp. Therefore, an Ionic Propulsion Blimp (using the blimp as the auxiliary lifting system) was developed and experiments were carried out to prove the operability of the Ionic Propulsion Blimp. In the future, an advanced control and navigation system will be integrated onto the Blimp, which will also be capable of wirelessly transmitting a real-time surveillance video to a ground station.

Acknowledgment

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