A laser-microfabricated electrohydrodynamic thruster for centimeter-scale aerial robots
Elma Dedic¹, Yogesh M Chukewad¹, Ravi Sankar Vaddi², Igor Novosselov², and Sawyer B Fuller¹

¹ Autonomous Insect Robotics (AIR) Lab, Department of Mechanical Engineering, University of Washington, Seattle, WA 98195, USA
² Novosselov Research Group, Department of Mechanical Engineering, University of Washington, Seattle, WA 98195, USA

* These authors contributed equally to this work.
* minster@uw.edu

Abstract

Interest in flying insect-sized robots is driven by their advantages over larger robots. Their small size and low weight allow for larger deployment numbers for greater coverage at the same cost. Flapping wings represent one means for generating lift, but this requires a complex and failure-prone mechanism. A simpler alternative is electrohydrodynamics (EHD) thrust, which requires no moving mechanical parts. Corona discharge generates a flow of ions in an electric field between two electrodes; the high-velocity ions transfer their kinetic energy to the neutral air molecules by collisions accelerating the gas in the direction of ion drift and creating thrust. Previous work reported a 30 mg aircraft able to lift its own weight that was fabricated from predominantly silicon components formed through reactive ion etching. To avoid the expense and time associated with that process, here we introduce an alternative fabrication process based on 355 nm laser micromachining. Our fabrication time, from raw materials to complete assembly, takes less than 25 minutes. Furthermore, our approach allows for greater flexibility in materials selection. Our four-thruster device measures $1.8 \times 2.5$ cm and is composed of steel emitters and a lightweight carbon fiber mesh. The device is 43 mg and measured thrust is greater than its weight.

Author summary

Agile small aerial robots can be useful in exploring areas where humans cannot reach. Applications of these robots include gas leak detection in pipes, search and rescue in case of natural disaster, etc. There have been recent developments in flapping wing robots at insect scale; however, these are mechanically complex; thus, fabrication of these robots becomes a challenge. Recently, researchers started working on developing aerial vehicles using electrohydrodynamic (EHD) thrust. The ions, produced during the corona discharge, interact with the neutral air molecules creating macroscopic EHD flow (also known as ionic wind). As there are no mechanically moving parts, this propulsion scheme eliminates fatigue failure as well as makes the robots more sustainable in case of crashes. In the current research, we demonstrate a rapid fabrication approach of a centimeter scale aerial robot which relies on EHD effect to propel itself. We present how these robots can be fabricated using widely available materials. In the end, we present a take-off of one of the designs of this robot with no moving part.
Fig 1. Quad-thruster robot. The $1.8 \times 2.5$ cm quad-thruster that weighs a total of 43 mg is shown. The robot components consist of a carbon fiber collector grid, four blue tempered steel emitters, and eight fiber optic glass tubes. All components are hand-assembled using external jigs. A U.S. penny is shown for scale.

Introduction

Insect-scale robotics has been an area of interest for its possible uses in agriculture, search and rescue, and biomedicine, among other areas. The small size and reduced manufacturing cost of insect robots have facilitated microrobotic research. To date, the primary emphasis in insect-scale robotics has been on drawing inspiration from biology, because biology has found solutions whose existence proves they work. One example is a flapping-wing robot fly [1]. Robots of this type have subsequently incorporated onboard sensors for flight stabilization [2] and wireless lift-off with power from a laser source [3]. Other developments include using explosives to break the surface tension of water [4] and RoboFly, which is capable of performing multi-modal locomotion including walking in addition to flying [5]. While flapping wings are well suited to insect-sized aerial vehicles, they impose a significant cost in terms of mechanical complexity [6]. In this paper, we focus on an alternative means of generating thrust that is not seen in biology: electrohydrodynamic (EHD) thrust. EHD thrust requires high voltage, which may be why it is not used in biology. From an engineering perspective, EHD has the appealing characteristic that it requires no moving mechanical parts, simplifying fabrication.

Our work here builds on the foundation laid by the “Ionocraft” developed by Drew et al. [7], a 3 cm four-thruster EHD aircraft. The “Ionocraft” was demonstrated taking off using an external power source. Though it is potentially simpler than a flapping-wing system, the EHD thruster in the ionocraft [7] was fabricated using expensive semiconductor-based clean room fabrication facilities. Significant engineering development is required before a small EHD-powered robot can perform aerial locomotion without wires and fully autonomously, which will be necessary for such robots to have a useful application. More rapid and less expensive methods to build the robots with EHD propulsion could facilitate a faster design iteration times, increasing speed the development of an autonomous version.

In this paper, we utilize laser machining fabrication to build centimeter-sized aerial robots with EHD trusters. The process allows for use of a greater variety of electrode materials and eliminates the need for a clean room facility. For example, it allows fabricating a complete four-thruster device in a matter of minutes. The quad-thruster
robot presented in this paper, as shown in Fig 1 is capable of generating thrusts exceeding its weight. We report a parametric study on the fabrication methodology and the EHD thruster measurements. The thrust and energy transfer efficiency are determined experimentally. Feasibility of using EHD thrusters for attitude control is demonstrated qualitatively.

The paper is organized as follow. First, we discuss the EHD effect and how it can be used to generate thrust in our robot design. The fabrication methodology proposed in this research is discussed next, which is followed by a discussion on design analysis and assembly where we present various parameters involved during the design and assembly of robots. Finally, we present the results of several EHD thruster experiments.

Electrohydrodynamics (EHD)

Electrohydrodynamics (EHD) is an interdisciplinary field describing the interaction of fluids with an electric field. Insights into complex multiphysics interactions are essential for understanding EHD flows: (1) the electric field from the potential difference between the anode and cathode and its modifications by the space charge effects; (2) the ion motion in the electric field; (3) the interaction between the motion of ions and the neutral molecules; and (4) the inertial and viscous forces in the complex flow.

Corona discharge driven flow

Corona discharge generates a flow of ions in a strong electric field between two electrodes; the high-velocity ions transfer their kinetic energy to the neutral air molecules by collisions that accelerate the gas in the direction of ion drift. This electrohydrodynamic (EHD) flow propulsion phenomenon, also referred to in the literature as ionic wind, is used in many practical applications, such as convective cooling \cite{8,9}, electrostatic precipitators (ESP) \cite{10}, plasma assisted combustion \cite{11}, airflow control \cite{12,13}, and as a turbulent boundary layer actuators \cite{14}. The corona induced EHD flow converts electric energy into kinetic energy directly and requires no moving parts. The voltage-current relation during the corona discharge characterizes the ion motion between the electrodes. This phenomenon has been studied since the early 20th century. The classic relationship was derived by Townsend \cite{15} in 1914 and validated for a coaxial corona configuration. Some recent studies modify Townsend’s quadratic relationship to better describe the relationship for different electrode configurations \cite{16,17,18,19}. A generalized analytical model for voltage to current and voltage to velocity relationship for EHD driven flow has been recently described \cite{19}; the analytical model has a good comparison with the experimental data in the accelerating flow regions (EHD dominated flow). Previous studies have studied that maximum velocity for point-to-ring electrode configuration was recorded at 9 m/s \cite{20} and have assessed the use of ionic winds in propulsion applications \cite{21}.

Stuetzer \cite{22} presented the first experimental and theoretical analysis of pressure drag produced by the ions, where he determined the pressure generation over a wide range of carrier media. Previous work performed by Masuyama \cite{23} determined the achievable thrust to power ratios of EHD propulsion on the orders of 5-10 N.kW$^{-1}$. Thrust to power ratio was found to be dependent on electrode distance and the potential difference between the electrodes. Similar results were observed for an ionocraft with a wireless power supply onboard and transmitted power upto 100 W to ionocraft at the voltages up to 12 kV \cite{24}. The EHD propulsion can be utilized for UAV propulsion; the experimentally measured maximum thrust density of 15 N.m$^{-3}$ was reported recently \cite{25}. Drew et al. showed that higher thrust density can be achieved for insect-scale robots \cite{7,20} and EHD flow can be used for flight control.
Electrohydrodynamic Force

A one dimensional model for an EHD thruster yields an expression in terms of the current, distance between the anode and cathode. Space charge effect is ignored here, however, it can be important at electric field strengths. The current is determined by integrating charge density

\[ I = \int J \, dA = \int \rho_e E \mu dA \]  

(1)

where \( \rho_e \) is the charge density, \( \mu \) is the ion mobility in the air, \( E \) is the electric field. Ion mobility value of \( \mu = 2 \times 10^{-4} \) m²/V-s is used here. For energy transfer efficiency analysis, consider that thrust is equal to the Coulomb force acting on the volume of fluid between the anode and cathode

\[ F = \int \rho_e E dV = \frac{I d}{\mu} \]  

(2)

where \( F \) is the thrust, \( I \) is the ion current, \( d \) is the distance between electrodes. The corona power can be written as in Eq. 3 and efficiency which is defined as \( F/P \) is given by equation Eq. 4.

\[ P = IV \]  

(3)

\[ \frac{F}{P} = \frac{d}{\mu V} = \frac{1}{E\mu} \]  

(4)

where \( E \) is the electric field strength, and \( V \) is the applied voltage. Drew et al. report the minimum efficiency in their design should be 2 mN/W. The analysis sheds insight into the importance of the electrode distance and applied voltage. Eq. 3 that for the larger electrode spacing higher efficiency values can be reached as observed by Guan et al. [20]. Related to electrode configuration, it is important to revisit Townsend’s relations [27]

\[ I = CV(V - V_{crit}) \]  

(5)

where \( V_{crit} \) is the onset voltage and \( V \) is the voltage applied. \( C \) is a constant related to the geometry of the electrodes. Thrust can be determined using Townsend’s relation

\[ F = \frac{C_1 V(V - V_{crit})}{d} \]  

(6)

where \( C_1 \) is a fitting parameter that depends on the geometry [23]. In practical thruster design to achieve maximum thrust, the constant \( C_1 \) needs to be maximized and \( V_{crit} \) needs to be minimized. Though the increase of distance between the electrodes would lower that thrust for the same operating voltage, the potential increase of the operating voltage above the critical value (this difference increases with electrode spacing) has a significantly greater effect on the thruster performance. Among the considerations related to the thruster design are the effects of non-linear ionization region, secondary flow structures, cathode blockage ratio, the transition from glow to streaming corona discharge and eventually to sparkover. The full optimization of the EHD thruster is beyond the scope of this paper.

Fabrication

Our fabrication process emphasizes speed and simplicity by minimizing the number of components, minimizing fabrication time.
Fig 2. Individual components of the quad-thruster robot. Top view of (a) an emitter drawing, (b) a quad-thruster collector grid drawing. (c) Jig-1 used for placing eight glass fiber-optic poles shown in (d) and also for keeping the grid in a plane perpendicular to the poles. (d) One of the eight poles required for the assembly. (e) One of the four emitters involved in the robot. (f) Jig-2 used for keeping emitters at a uniform distance from the grid. (g) A quad-thruster grid from an earlier version where the center gap is smaller as compared to that in (b).

In [26] fabrication takes place in a silicon-on-insulator (SOI) process. The emitter and collector electrodes are made from silicon patterned with a photolithographic mask. After a deep reactive ion etch (DRIE) process to cut through the wafer, the electrodes are once more etched with hydrofluoric acid (HF). In that work, insulating standoffs to separate the emitter from the collector were made from fused silica capillary tubing with an outer diameter of 400 \( \mu m \) and an inner diameter of 375 \( \mu m \). Connections between the tubing and electrodes were made with UV-curable epoxy. Power connections are made with the application of silver epoxy. An external jig was used to align the assembly. The most recent reported design for the “Ionocraft” has 41 components (including sensor components) [7].

Here, we use laser micro-machining instead of lithographically-patterned silicon. Our laser is a diode-pumped solid-state (DPSS) frequency tripled Nd:Yag laser with 355 nm wavelength (PhotoMachining, Inc., Massachusetts). The DPSS laser output power is 2 W, its beam diameter is 20 \( \mu m \), and position repeatability is about 3 \( \mu m \). With this system, we are able to machine both the emitters and collector in about ten minutes. Our proposed methodology involves machining using the following steps:

1. Stainless steel shim and carbon fiber sheet are laser machined with features for emitters and grid respectively, using the DPSS laser. Their corresponding CAD drawings and actual machined parts are shown in Fig. 2 (a), (b) and Fig. 2 (e), (g), respectively

2. Jig-1 and jig-2 (Fig. 2 (c) and Fig. 2 (f), respectively) are fabricated out of a sheet of acrylic using a standard CO\(_2\) laser cutter.

3. Poles made out of glass fiber optic tubing of an inner diameter of 250 \( \mu m \) and an outer diameter of 350 \( \mu m \) are used for maintaining a uniform gap between the electrodes. One of the poles is shown in Fig. 2 (d).

Design Analysis

In this section, we discuss various parameters involved in the design and assembly of the robot. We walk through design considerations to optimize the thrust generated while selecting values for these parameters.
Emitter

The emitter (corona electrode) material must be rigid, conductive, and with high curvature features (points). The design analysis of the emitter electrode included material, curvature, number of emitter tips, and orientation.

The material initially used was a 50 µm stainless steel but was changed to a 100 µm blue tempered stainless steel as it was a stiffer and more durable material. We explored different tip angles, starting with 30°, before reducing to 10° and then 5°. A smaller radius of curvature of an emitter tip creates a stronger electric field gradient and a higher concentration of like charges. Due to the limitations on the laser beam diameter used to fabricate the emitter and local heating due to the beam, we found that 5° was the sharpest tip that the machine could fabricate.

The number of emitter tips corresponded to the number of electric field localizations for corona discharge to occur. We explored different numbers of tips. In each case, the thruster showed similar thrust values, so we settled on eight tips. The last factor evaluated was the emitter tip orientation. The emitter design in the baseline iteration had electrode tips that were designed to be in the plane parallel to the collector grid. This case involved ions having an initial velocity component in the horizontal direction.

It was concluded that the horizontal velocity component and hence the kinetic energy loss can be avoided by pointing the tips directly towards the grid. This improved thrust from 60 µN to 105 µN.

Collector

The collector is the heaviest of all the components in the robot. It must have a low blockage ratio to allow the thrust-causing air molecules to flow through it, while remaining stiff. We explored different grid spacing and material thicknesses.

We started with a collector grid with 150 µm spacing between grid marks made out of readily available 50 µm stainless steel (Mc Master-Carr). Due to issues with weight and bending of the stainless steel grid from strain of other components, we switched to unidirectional carbon fiber reinforced composite. The carbon fiber sheet was made by laying up the 69 GSM (69 g/m²) carbon fiber (TenCate M49J) in 0-90-0 directions. After curing, this lay-up measures about 180 µm thick. The mass of the single thruster carbon fiber grid with this configuration was 5.9 mg, compared to the previous 8.3 mg stainless steel grid. We further optimized spacing and weight by reducing the spacing from 150 µm to 100 µm. We were unable to achieve a functional collector using thinner, 90 µm carbon fiber and reduced grid spacing of 50 µm because of excessive breakage during fabrication.

Quad-thruster design

After individual thrusters were designed, the next design steps involved putting four of the single thrusters together to make a quad-thruster. In the quad thruster, each single thruster was separated by 7 mm. We also created a single thruster, as shown in Fig. 3, for testing and characterization.

Assembly

In this section, we discuss the assembly process for the quad-thruster. The assembly takes about 15 minutes to complete after the components are fabricated. The steps involved in the assembly process are summarized below.

1. The set of four poles are placed through holes on jig-1 as shown in Fig. 4(a).
2. The grid is carefully placed on jig-1 through the poles, it is then glued down with these poles from top to avoid accidentally gluing poles of the grid with the jig. It then looks as shown in Fig. 4(b).

3. Four of jig-2 designs are now placed on each single collector grid as shown in Fig. 4(c).

4. Four emitters are now slid into the poles on top of single collector grids as shown in Fig. 4(d). It is made sure that all of the tips are in contact with jig-2. These emitters are then glued down with the poles.

5. Once the glue is dry, all four jig-2s are slid out, and the whole assembly is then taken out of jig-1. The assembly looks like the CAD shown in Fig. 4(e). Fig. 4(f) shows a picture of an actual assembly sitting on a jig-1.

6. The whole system is powered through external tethers. The quad-thruster has 5 external wires; a 51-gauge copper wire is attached to each of the four emitters and to the collector grid. Each wire is wrapped around the corresponding electrode, and some conductive epoxy is added using a probe tip to secure the joint.

**Experimental Results**

The experimental apparatus consists of a high voltage power supply, a precision scale to measure thrust, and ceramic insulated tweezers to hold the robot. The experiments are divided into two parts—1) measure thrust, and 2) perform a free flight. A diagram of the apparatus for the former is shown in Fig. 5. The thruster in its inverted orientation is attached to electrically insulating ceramic tweezers, which are placed on a precision scale (Mettler Toledo). The scale reading is reset to zero (tared), and voltage is applied...
Fig 4. **Assembly steps of the quad-thruster robot.** (a) Fiber-optic glass poles placed into the holes on the Jig-1. (b) Grid is then placed on jig-1 through the poles. Note: grid thickness exaggerated for 3D view. (c) Four jig-2 designs placed on each single collector grid. (d) Four emitters are slid into the poles on top of jig-2 designs. (e) Dimetric view of a quad-thruster after the jigs are removed. (f) Picture of a quad-thruster fully assembled in the external jig-1 that is used for assembly.

across the electrodes of the robot. Thrust force is measured by the reading on the precision scale. We confirmed that the off-center force did not affect the accuracy of the measurement by confirming that a mass placed at the center of the scale produced the same reading as one placed at the location of the thruster at the tips of the tweezers, which it did.

The robot was released from the ceramic tweezers for the latter part when we performed a free flight. This was performed by hanging the robot by its power tethers (51 gauge insulated copper wires).

Because of fabrication variations, each thruster in the four-thruster device generated a different thrust at a given voltage. For this reason, we decided to focus on a single thruster robot first to perform thrust measurements.

Fig. 6 shows how the thrust changes with the applied voltage across the electrodes. We performed this experiment for three cases: 1) emitter perpendicular to the grid plane, 2) emitter parallel to the grid plane with stainless steel grid, and 3) parallel emitter with carbon fiber grid. It can be seen that the thrust increases with increasing voltage applied across the electrodes. The maximum thrust generated occurs immediately before sparkover is initiated, at which point thrust drops to zero. The trend of thrust vs.

Fig 5. **Schematic of thrust measurement apparatus.** Thrust generated by the EHD thrusters was measured using a precision scale. The thruster, in its inverted orientation, was held using a ceramic insulated tweezer. Tethers are not shown for simplicity.
Fig 6. Single thruster—thrust vs voltage applied. Thrust vs applied voltage for a micro-thruster with the emitter tips perpendicular to the collector compared to two micro-thrusters with the tips parallel to the grid.

Voltage is roughly linear. The mass of the device is about 10 mg. In the case of emitter perpendicular to the grid plane, results show that the thrust generated is large enough to be able to lift the weight of the single thruster itself. However, the thrust turned out to be less than the thruster weight for the parallel emitter. This can be attributed to the path of the ions starting from the emitter being perpendicular to the vertical axis first. This leads to collisions with air particles in a horizontal plane which represents a loss of kinetic energy in the lateral direction that could have been used to generate vertical thrust.

Once the single thruster is seen to be generating sufficient thrust, we let the single thruster robot hang freely and manually increased the voltage to see it taking off. Fig. 7 shows a set of images from this takeoff. These images are taken at a uniform interval of one second while increasing the voltage. The robot is seen to be achieving a total height roughly equal to twice its body height.

Now, we consider a quad-thruster with emitter tips perpendicular to the grid for a similar type of experiments. The total weight of the robot is about 43 mg. Fig. 8 shows that each thruster, when tested individually while applying no voltage to the other electrodes, generates about 11 mg of thrust. This compares well with the case of

Fig 7. Frames from single thruster flight. Frames captured at a uniform interval of 1 second from a single thruster in flight. Robot is attached and hanging by its power wires.
Fig. 8. Quad-thruster—thrust vs voltage applied. Thrust values for single thrusters for variable applied voltages. The input voltages range from 2.5 kV to 4 kV. Some of the individual thruster increase in thrust with a smaller amount of differential voltage applied. This shows that each thruster follows the same roughly linear trend but does have a different input needed.

...the single thruster robot. However, these thrusters are seen to be operating optimally at different voltages. Therefore, a different voltage must be supplied to each thruster to equalize their thrusts. This will be necessary to achieve a vertical takeoff.

Thrust density and efficiency are important parameters in understanding the working and performance of EHD thruster compared to other designs. Thrust density is defined as the amount of thrust generated per unit area, whereas efficiency is defined as thrust per unit power. Thrust density for EHD thrusters is calculated from the effective area where EHD flow exists, i.e., the mesh area. The force exerted by the fluid is measured using a precision scale. A maximum thrust of 0.137 mN which corresponds to 8.15 N/m² thrust density achieved at an input electrical power of 200 mW. Therefore, the thrust density per unit power for the EHD thruster is 40.8 N/m²W at the point of lift-off. The efficiency is about 0.69 mN/W. The data can be compared to a piezo-actuated flapping wing such as the RoboFly [5], which has a measured efficiency of 12.2 mN/W. For a thrust of 0.736 mN, input power of 60 mW, and 308 mm² effective swept area of wing, the thrust density is 2.39 N/m². Therefore, the thrust density per unit power is 39.8 N/m²W. Therefore, while the efficiency of the EHD thruster is lower than a flapping-wing robot of comparable size, the thrust density per unit power consumed is almost equal. This is important because the thrust density correlates to the mass of the thruster, and therefore this metric represent scale-independent (and propulsion-type-independent) measure of efficiency.

Fig. 9 shows how thrust density varies with corona input power of the EHD thruster. Corona power was by multiplying anode voltage and current. The power supply provides an output indicating the current load. The thrust was directly measured using a precision balance as described in Fig. 5. It was previously shown that anode current does not vary linearly, but instead quadratically with the applied voltage [15, 19, 27], and our measurements match this prediction.
Conclusion and future work

Our results indicate that UV laser micro-machining represents a viable and much faster alternative to a silicon-on-insulator fabrication process of an EHD thruster. As shown in Table 1, we were able to fabricate a complete device, from raw materials to complete assembly, in about 25 minutes. This compares favorably with the process reported in [7], which takes 2-3 days at best. Their fabrication time includes next-day shipping time for the masks and other queue time. Therefore, our work represents a potentially much faster means to fabricate EHD thrusters. In addition to short fabrication time, we remark that laser micro-fabrication allows for a much more diverse material set. While silicon has a high strength-to-weight ratio, there are other materials that can provide better performance for certain applications, such as the even higher strength-to-weight ratio of unidirectional carbon fiber composites. Furthermore, if there are other materials that may improve the lifetime of the sharp emitter tips, it is almost certainly possible to machine it using a DPSS laser. Lastly, the fabrication of these electrodes also does not require a clean room facility.

Our results give a strong indication that the single-thruster design was able to lift its own weight, as indicated by thrust measurements and free-flights connected to a wire tether. The thrust-to-weight ratio of our final thruster design presented here is about 1.4, which is below the ratio of 4 reported in [28]. In order to get sensors and power supply on-board as a step towards full autonomy, our robot will need to generate more thrust for lift-off before sparkover occurs. We used fewer emitter tips than [28], and we expect that increasing that number, as well as adding rows of tips, will substantially increase lift with little added weight. We also believe there is ample opportunity to reduce the mass of our device through the use of thinner and lighter material. In future work we plan to conduct an exploration of different designs in finite element simulation to explore the configuration space in greater detail.

To achieve a vertical lift-off of the four-thruster device will require multiple, different high-voltage sources so that thrust is equalized. For flight control, a four-channel circuit that is also capable of changing voltage with high bandwidth >1kHz will also be needed.
Fig 10. Quad-thruster– free-body diagram Free-body diagram of a quad-thruster in a side view to demonstrate the pitch control. Thrust generated by i-th thruster is denoted by $F_i$. For positive roll angle, $\theta$, $F_1+F_3$ and $F_2+F_4$ can be controlled actively to stabilize the robot at a desired $\theta$.

Table 1. Comparison of this work with earlier work by Drew [7].

|                          | Drew [7]                  | This work         |
|--------------------------|---------------------------|-------------------|
| Electrode Material       | Silicon                   | Carbon fiber (grid) |
|                          |                           | Stainless steel (emitter) |
| Fabrication time (excluding assembly) | 2–3 days            | 10 minutes        |
| Total weight (mg)        | 30                        | 43                |
| Assembly time in minutes | 30                        | 15                |
| Clean-room facility      | Required                  | Not required      |

Comparison of electrode material, fabrication time, total weight, and the requirement of a clean-room facility. Our design balances weight and distinct parts to facilitate more rapid fabrication.

We anticipate the controller for the quad-thruster will be similar to that of the four wing insect scale flapping wing robot developed in [29]. The free body diagram for the pitch dynamics is mentioned is shown in Fig. 10. Similarly, roll motion can also be controlled using voltage differentials. Controlling the yaw motion is left for future work. Pitch dynamics is described as follows.

\[
\begin{align*}
I_p \ddot{\theta} &= [(F_2 + F_4) - (F_1 + F_3)]l \\
m \ddot{z} &= [(F_2 + F_4) + (F_1 + F_3)] \cos \theta - mg \\
m \ddot{x} &= [(F_2 + F_4) + (F_1 + F_3)] \sin \theta
\end{align*}
\]

Derived from Fig. 10 where $I_p$ is the moment of inertia of the robot about the pitch axis, $\ddot{\theta}$ is the angular acceleration, $m$ is the mass of the robot, and $F_i$ is the thrust force generated by i-th thruster. This shows that by varying thruster forces $F_i$, the robot is fully controllable in the $x-z$ plane.

A successful flight of a 5 pound plane using only EHD to generate thrust is reported in [30]. The emitters are thin wires that are strung at one end and collector wires that are thicker on the other end of the aircraft. With the simplification of fabrication of electrodes and speed of fabrication for an EHD thruster, this process could be replicated. A larger scale thruster could serve as an aircraft and the take-off requirements would
remain simple and assembly time could be improved so that efforts could go toward producing more of these robots at faster rate. Though production on a large scale would be different, the same improvements that were made for micro-thrusters could be applicable to a different scale.

Other than changing the scale of the EHD thrusters, components can be implemented as payload on the quad-thruster. A small on-board camera can be added which can be helpful in the steps towards controlled flight and sensing around surroundings, as demonstrated in [31] for a flapping wing insect-scale robot. Future work also includes work on the connections for power for this robot. Until recently, micro-robots have been powered through external connections. The Autonomous Insect Robotics Lab at the University of Washington has developed light weight circuit that requires no battery and provides wireless power to a robot [3]. This circuit was capable of developing 200 V to drive piezo actuators in a 100 mg package. We expect that a similar approach could extend to the kV potential differences needed for EHD thrusters.

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