Smart Agriculture using Flapping-Wing Micro Aerial Vehicles (FWMAVs)

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Abstract. One of the main domains of Smart Agriculture is Smart Artificial Pollination using MAVs. With their body size and dimensions, they show promise of filling in the void left by absence of insect pollinators. This study would suggest an improvised version of the previously designed insect-scale flapping-wing micro air vehicles (FWMAVs), namely a Harvard RoboBee-like two-winged robot and the four-winged USC Bee+. This version would attempt to solve the issue of low controllability which is observed in the previous prototypes developed so far which render them inefficient for practical applications like artificial pollination. We aim to do this by reducing the number of actuators to just one and removing dependency on wing-movement for pitch, roll and yaw by controlling the system using weight shifting mechanisms with the help of electromagnetism. We attempt to implement and prove that this is would be a viable and easier method for this problem, since the control system efficiency increase. This would also reduce material and manufacturing costs due to its simple design and less number of parts required, almost halving the number of materials required in the mentioned designs. This paper is the first of its kind where we show a fully functional and able FWMAV structure application for Artificial Pollination.

Keywords: aerial robotics, microbotics, actuators, IoT, smart farming

1 Introduction

Bees and Humming birds have always been the center of attention when it came to extremely accurate contrallibility and precision. To replicate an automated model of them would be to construct a perfection incarnate aerial vehicle. The size of the robot would also be extremely useful when it comes applications like artificial pollination, disaster management, search and rescue operations, military, etc.

Harvard RoboBee [2] and USC Bee+ [3] have been one of the the most developed designs in this area, however, there are still challenges in terms of stability and controllability: due to the fact that they depend heavily on an actuator for each wing that beat with variable frequencies in order to cause an imbalance in equilibrium and make the robot move in a certain direction.

Since these frequencies have to be changed at millisecond instances, having high precision control would be a challenge.

We aim to solve this problem by using a single actuator and removing dependence on wings alone for maneuvering and instead propose a model which changes direction by a weight shifting mechanism. The model would have both the wings beating at same frequency and would determine the thrust of the body, while the roll and pitch would be determined by a tiny weight attached to the robot at the bottom which would be fixed with a planar joint. This is exactly similar in structure to the first of this type which was designed and termed the HMF [1].

We developed the model in ROS using python and then deployed and simulated in Gazebo.

The solution we provide, will be easy to implement in a smart agriculture system for not only artificial pollination, but also various other applications such as plant health monitoring, etc. This model is simpler in structure, more robust and less power hungry compared to its counterparts in [2] and [3].

We first show the kind of methodology and approach we adopted, the additional features we added to the HMF[1], theoretical proof of our concept and the results of our experiment.

2 Smart Agriculture using IoT - Related Work

Smart Agriculture is an emerging concept that helps in managing farms using modern technologies to increase the quantity and quality of products while optimizing the human labor required. It is a big leap from traditional farming as it brings certainty and predictability to table. Application of Internet-of-Things (IoT) in agriculture could be a life-changer for humanity and the whole planet.

On farms, IoT allows devices across a farm to measure all kinds of data remotely and provide this information to the farmer in real time. It is capable of providing information about agriculture fields and then act upon based on the user input. This paper aims at making use of evolving technology i.e., IOT and smart agriculture using automation. Together, they will be paving the way for what can be called a Third Green Revolution.

The most common IoT applications in smart agriculture are sensor-based systems for monitoring crops, soil, fields, livestock, storage facilities, etc.

Currently, we witness how extreme weather, deteriorating soil, drying lands and collapsing ecosystems make food production more and more complicated and expensive. It is projected that there will be more than 9 billion people inhabiting earth by 2050 which necessitates large scale food production.

Smart agriculture based on IoT is focused on helping farmers close the supply demand gap, by ensuring high yields, profitability, and protection of the environment. Monitoring environmental conditions is the major factor to improve yield of the efficient crops.

Therefore, smart farming has a real potential to deliver all the needs in a safe,environmentally friendly and resource-efficient approach. Moreover, it is a true way to scale down on the use of pesticides and fertilizer. This allows getting a cleaner and more organic final product compared to traditional agricultural methods.

The ultimate result from this automated smart farming process would be a high precision and control, eventually leading to considerable savings in all key resources.

Sushanth and Sujatha [6] propose a system that responds to the user input with the help of wireless communication 3G/4G. The system has a duplex communication link based on a cellular-Internet interface programmed through an android application that can be used to communicate with the beebot.

Multiple projects in the area of Smart Agriculture using IoT have been carried out. In [7] algorithms are developed algorithms for predicting and monitoring plant health. [8] proposes a network of sensors for smart irrigation. [9] proposes better image acquisition algorithms based on cloud computing were developed to solve problem of blurred image taking by mobile robots involved in smart farming. All of these assert to the bright future of smart agriculture and IoT being the solution to many agricultural problems.

3 Smart Agriculture using Beebots - Proposed Vision

Agriculture is the one of the largest source of livelihoods in India. It plays a crucial role in the economy. But there are some challenges being faced by the farmers. There are increasing pressures from climate change, soil erosion, and biodiversity loss and fulfilling the demand and dealing with farming works —plants, pests and diseases. Hence smart farming combat some of them and allows farmers to grow crops in a more controlled and productive manner.

Research has shown that the presence of wild bees increases yields across many types of crops. The vast majority of plant species—almost 90 percent, in fact—rely on pollinators to reproduce. This means bees are responsible for one out of every three bites of food we eat. As pollinators, bees play a part in every aspect of the ecosystem. But there is a decline in bee population. There are many factors that contribute to pollinator decline — most of which are related to the climate crisis. Pesticides, fertilizers, parasites, biodiversity loss, deforestation, changes in land use, and habitat destruction are just a few of the reasons.

According to [10] and [11], pollination by honeybees and wild bees significantly increased yield quantity and quality on average up to 62 percent, while exclusion of pollinators caused an average yield gap of 37 percent in cotton and 59 percent in sesame. When we combine that with artificial pollination methods and make a robotic bee, efficiency in crop yield is bound to increase significantly.

This paper discusses the framework for next generation farming based on a combination of precision agriculture and robotic systems. The work focuses on using robotic bees in agriculture. This paper hence is first of its kind where it applies the application of Flapping-Wing Micro Aerial Vehicles (FWMAVs) in Artificial Pollination specifically and Smart Agriculture generally by proposing more applications in the field. The beebot can be equipped with a structure enabling artificial pollination, equipped along with the database of the farm, helping far more efficient form of pollination than hand pollination or actual bees. Futuristically, as suggested in [6] the beebot can be further equipped with visual sensors and converted into an IoT, which accesses the online database, helping to generate an outcome value/expected yield, health parameters of each plant in the farm, etc., as envisioned in Fig. 1, where Beebots can be released in a desired area which are constantly connected as IoT devices to a common server for instructions and access to cloud computing, database, etc. Based on above obtained values the Beebot can also identify which crops can be planted for the next season cycle.

The paper identifies problems of system adaption, usability, and feasibility, health of plants and users and energy consumption. The precise implementation and use of the model will make agriculture more profitable, efficient, environmental friendly and help make the most appropriate decisions.

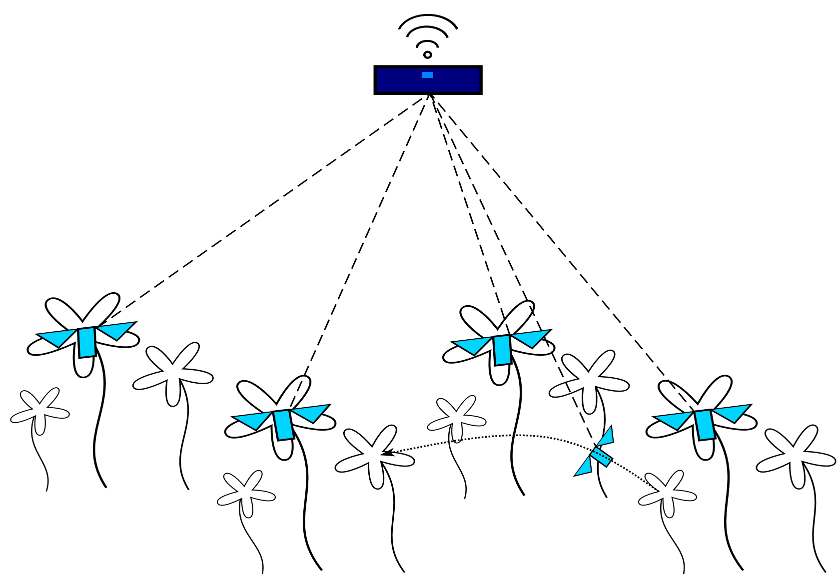

Fig. 1: A Beebot based IoT system for artificial pollination

In [4], a clear picture and mechanism is constructed which shows how MAVs would perfectly fit within the umbrella of Smart Agriculture, how MAVs would be extremely efficient in collecting data, pollinating and monitoring, functioning as vital IoT devices in the whole structure. Robotics, automation, and cloud software systems are tools for smart farming.

4 Proposed Beebot

Most of the mechanical design is extremely simple to manufacture. The body primarily consists of five components in total. Four of these are similar to the base model as proposed in [1]: the exoskeleton, transmission, wings, and actuators. In addition to that we add a small cap like structure to the bottom of the exoskeleton for carrying out the weight shifting mechanism.

4.1 The Exoskeleton

The exoskeleton or the air frame is primarily made of carbon fibre, which is light weighted and strong, ideal in case of an FWMAV. The structure is a hollowed out cuboid with some faces cut out. It would contain the actuators, weight shifting mechanism, and transmission.

4.2 The Wings

The wings are made of more flexible material so as to be able to bend to provide the thrust. The wings are composed of a structural frame and spars(veins) made from carbon fiber and the membrane made from polyester film. The materials are chosen such that they remain rigid under various flight condition. Each wing is 1.4 cm long, and along with the Exoskeleton, the wingspan amounts to just 3.1 cm.

4.3 Actuation

The actuator chosen for this application is a bio-morph piezoelectric actuator. These actuators are chosen because of the fact that in their normal mode of operation have too short a stroke to be useful for micro-robots. They can respond at high frequencies, many small displacements can be added together to give large net motion.

4.4 Transmission

The wing stroke is directly controlled by the actuator and transmission .Wing rotation takes place with a flexure joint in between the output of the transmission and the wings .This flexure is parallel to the wingspan direction and the joint takes care of over rotation of the wing. This system is actuated in only one degree-of-freedom

4.5 Weight shifting mechanism

A tiny weight put in a cap is attached to the bottom of the body of the robot. The cap has four electromagnets which control the x- and y- coordinates of the weight within the cap. This enables weight shifting and hence resulting in the tilting of the body of the robot.

5 Proposed Design

In order to come up with the design, we start with the basic model designed and published in a paper [1]. It was capable of only a single vertical degree of freedom. Building on top of it, we decided to go the simplest way possible and concluded with the weight shifting mechanism as an viable solution. This method would solve the disadvantages other designs presented in maneuverability without at the cost of increased power loss as is the situation in other models. We just add a small weight at the bottom of the body and shift it to shift the centre of mass of the whole robot resulting in a title and hence developing a horizontal component to the thrust generated by the wings.

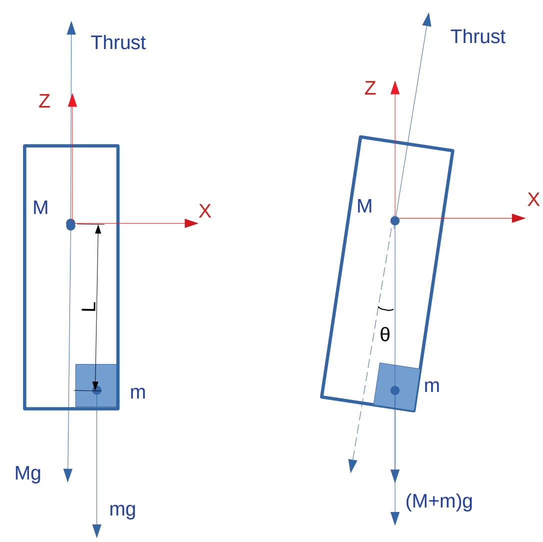

Fig. 2: Illustration of weight shifting mechanism

5.1 System Dynamics

The net force exerted by the wings on the body is balanced by sum of the weight of the body and the resultant thrust as

$$m\ddot{r} = -mgn_3 + fb_3 \tag{1}$$

where b_3 is vector along the axis of the body and n_3 vector along universal $z-axis$ and r is the resultant force vector.

Change in Orientation:

$$\dot{q} = \frac{1}{2} q * p \tag{2}$$

Rotational Force:

$$J\dot{\omega} = -\omega \times J\omega + \tau \tag{3}$$

5.2 Actuator Command Generation

Let m be mass of the smaller shifting weight and M rest of the mass of the body, which results in the tilting of the body by an angle θ. In equilibrium conditions, for F representing the thrust generated by the flapping of wings on the body,

$$F \cos\theta = (M + m)g \tag{4}$$

where body tilt angle, θ is

$$\theta = \arctan \frac{x_{COM}}{L} \tag{5}$$

Where L represents vertical distance between Centre of Mass and the smaller mass m and x_{COM} represents shift in Centre of Mass due to shifting of weight by distance x from (0,0). x_{COM} is calculated as

$$x_{COM} = x \frac{m}{M + m} \tag{6}$$

Similarly along Y axis.

While the horizontal component provides for motion.

$$F \sin\theta = (m + M)a \tag{7}$$

Hence we can control two parameters, F and x.

F is directly proportional to the speed of flapping of wings and can be input as a product of height required and a constant K.

x will be run through a PID controller to determine how fast and in which direction the body will move in.

5.3 Weight Shifting Mechanism

To be able to displace the weight m through an amount x, we use Electromagnetic force. The electromagnetic force generated

$$F = \frac{\mu_o}{4\pi} \frac{m_1 m_2}{r^2} \tag{8}$$

Considering two electromagnets opposite to each other with magnetic poles m_1 and m_2 at a distance of r units from each other attached to the edge of the cap.

So, force by first electromagnet is given by

$$F_1 = \frac{\mu_o}{4\pi}\frac{m_1 m_i}{x^2} \tag{9}$$

and force by second electromagnet by

$$F_2 = \frac{\mu_o}{4\pi}\frac{m_2 m_i}{(r-x)^2} \tag{10}$$

where r is the diameter of the cap, x distance required to move, m_i the induced magnetic moment in the weight, and m_1 and m_2 are the magnetic moments of the two electromagnets. Net force would be a difference of these two forces resulting in acceleration of the small weight

$$F_{resultant} = F_1 - F_2 = ma \tag{11}$$

where a is the acceleration and m mass of the weight.

Now to move the weight through a distance l,

$$l = \frac{at^2}{4} \tag{12}$$

for a zero initial velocity, considering an immediate deceleration of the same amount after $t/2$ time has passed.

5.4 Attitude controller

Based on the information regarding orientation of the body received from the IMU, we run the following control loop.

$$Roll = e_r K_p + K_i \int e_r dt + K_d \frac{de_r}{dt} \tag{13}$$

where e_r represents the error in roll, i.e., the difference between the desired orientation and current orientation, K_p, K_i, and K_d represent PID gains.

$$Pitch = e_p K_p + K_i \int e_p dt + K_d \frac{de_p}{dt} \tag{14}$$

where e_p represents error in pitch.

Now, we define the amount of change in position of the weight along x-axis and y-axis as

$$x = Roll - Throttle \tag{15}$$

$$y = Pitch - Throttle \tag{16}$$

which is then used to calculate the required force and electromagnetic field induction by Eq. (12) and (11)

5.5 Position controller

Position controller is comprised of two sub-algorithms. The first sub-scheme generates the magnitude of the thrust force, f; the second sub-scheme generates the desired attitude. In specific, f is computed as

$$f = f_a^T b_3 \tag{17}$$

$$f_a = -K_p(r - r_d) - K_d(\dot{r} - \dot{r_d}) - K_i \int (r - r_d)dt + mgn_3 + m\dot{r}d \tag{18}$$

where K_p, K_d, and K_i are positive definite diagonal gain matrices; and r_d is the desired position of the robot's center of mass.

5.6 ROS and Simulation

The system includes the CAD design translated into URDF which represents the physical and collisional properties of the model. A feedback controlled control system is designed taking input from the body of the robot and giving output as torque required to apply on the joints.

The basic architecture, as shown in Fig. 3, of the MAV includes a control system node which publishes input values to the simulated Beebot body in Gazebo which also intakes input from the simulation's physics' node providing for external influences like wind, gravity, collision, etc. The simulated sensors record data which is processed by a state estimator and the processed feedback is given back as input to the control system node.

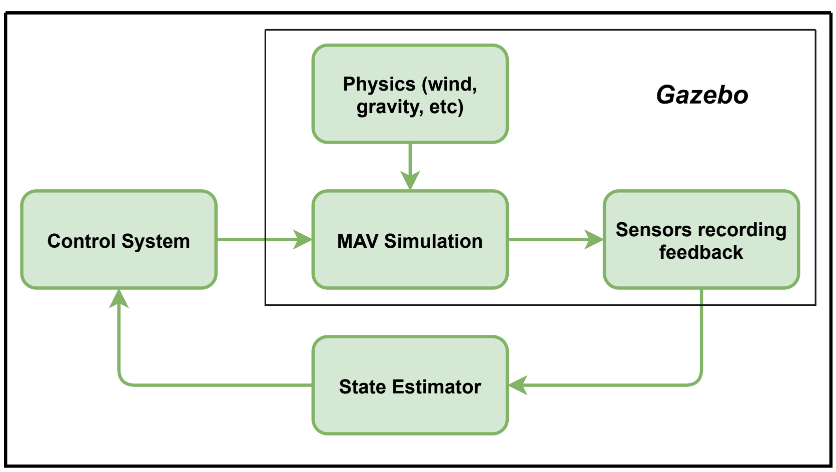

Fig. 3: Proposed Beebot ROS architecture

The architecture of ROS nodes and ROS topics has been quite simple and intuitive. The robot was designed as a simple cuboid with two wings attached by hinges. the wings themselves can rotate in order to properly provide for thrust as shown in Fig. 4.

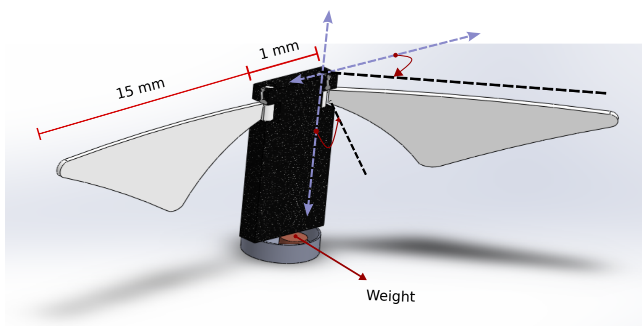

Fig. 4: Structure of the Beebot

Each hinge and wing has a joint each, making it total four joints. Every joint has its own topic declared on which command is published. A single node containing the control system algorithm, takes in the position and state of the wings as inputs and gives command to the joints in a feedback controlled loop structure as shown in Fig. 5.

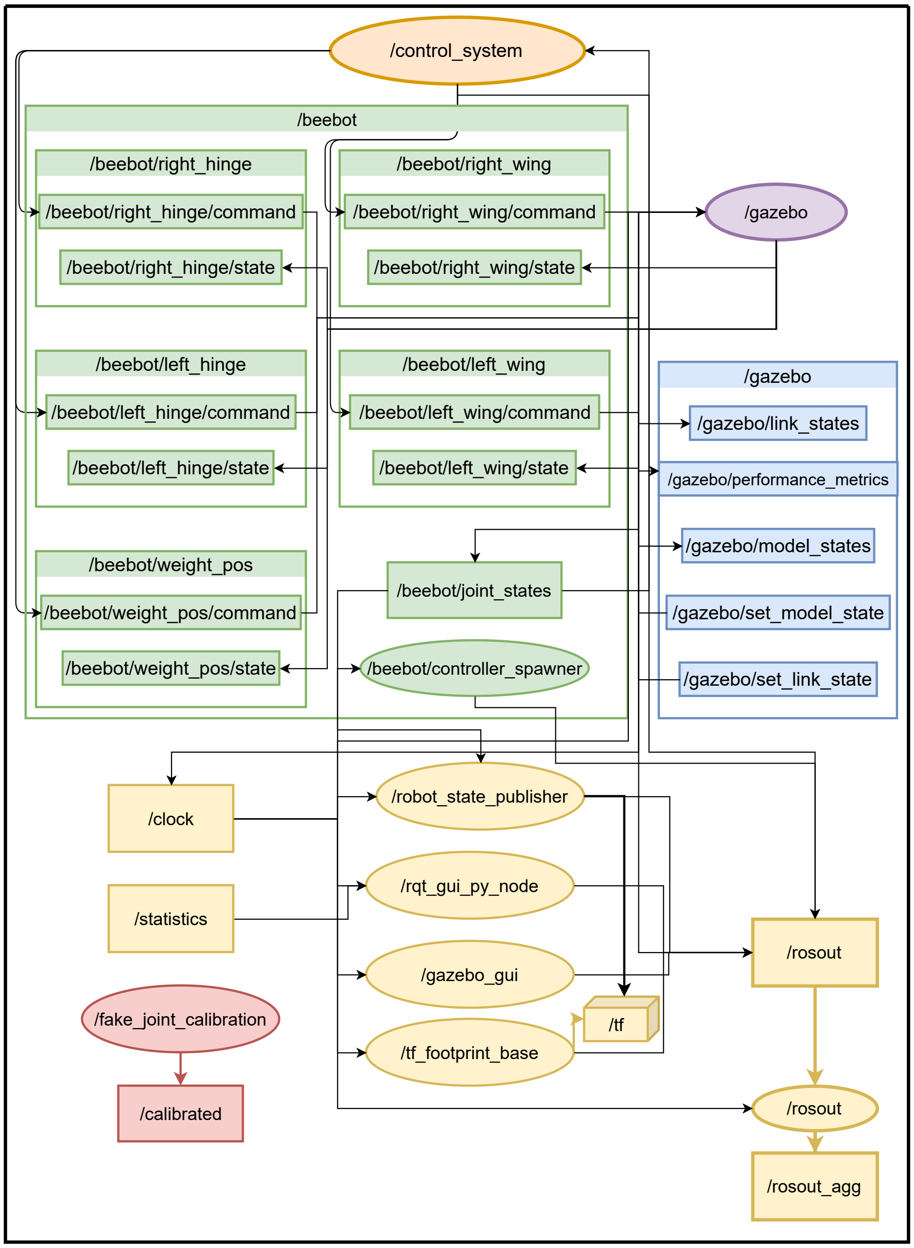

Fig. 5: Flow Chart of the ROS architecture used for simulating

As shown in the Fig. 4, a forward flap would not only mean yaw movement of the wings but also a negative pitch. Similarly for a backward flap, a negative yaw along with a positive pitch.

6 Experimental Results

We prototyped and tested the control system algorithms using ROS and Gazebo. The prototype has a wingspan of 3.1 cm and weight of 145 mg. Each wing is 15 mg, the additional weight structure 30mg, and the body itself 85 mg. We tested a wide range of values for taking off and landing, and successfully managed to fly vertically, hover the robot and tilt it in the desired direction.

6.1 Flight

The flapping frequency observed was 150 Hz at which the robot took off at a reasonable speed.

The graph in Fig. [6] represents the take-off mode with the command given in terms of Newton-meters and the wing responding accordingly measured in radians.

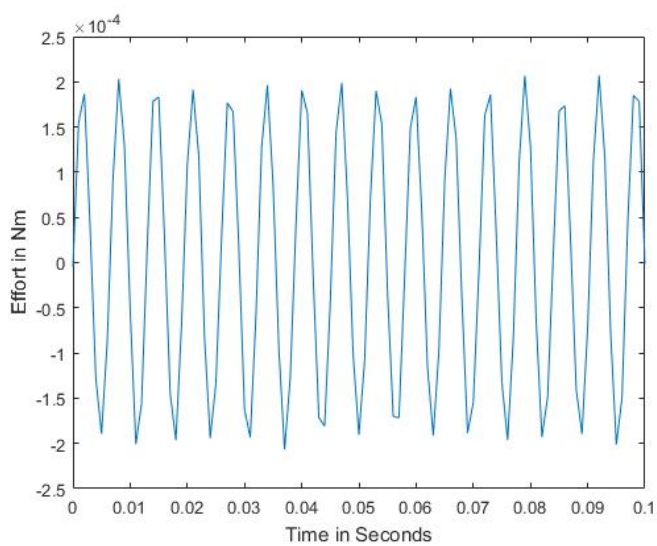

Fig. 6: Input values for the wings

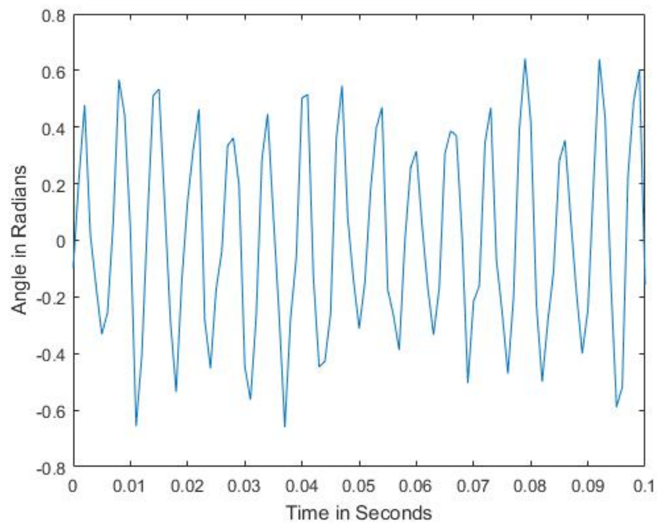

Fig. 7: Flapping Pattern

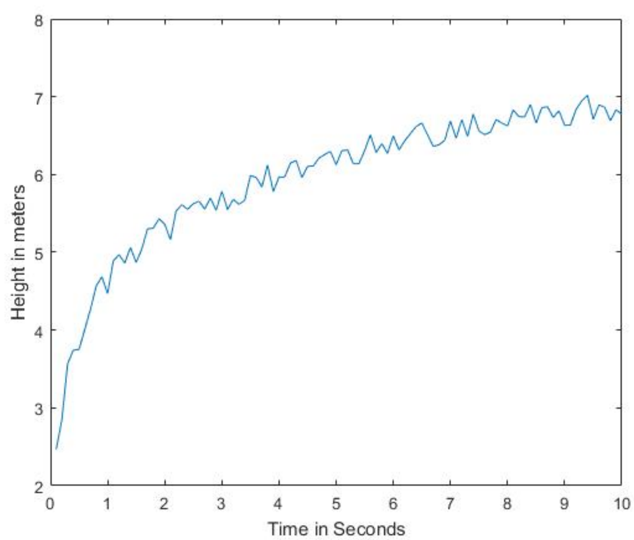

Fig. 8: Graph representing change in height of the Beebot as it flies vertically and stops at a height of 7 meters

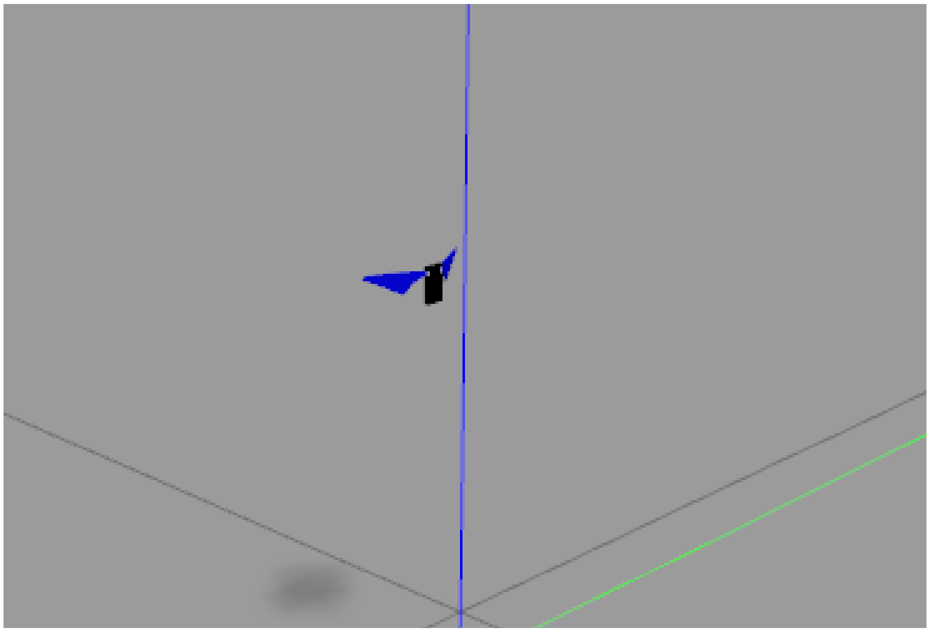

Fig. 9: Gazebo Image

6.2 Hover

Fig. 8 represents the position of the Beebot as it tries to stabilise itself at a point in the Simulation at a height of 7 meters at a flapping frequency of 120 Hz.(Fig. 9).

6.3 Tilt

After adding the extra weight, we set to trying to get the robot body to tilt. We had the body tilting at roughly 30^o as shown in Fig. 10 and Fig. 11. This was done by keeping the additional weight in a cap attached to the bottom of the body, with its weight being roughly $30mg$. The weight moved at a distance of 2.5 mm within the cap to achieve this value of tilt.

This shows how—instead of [2], where a complex and power hungry control system was implemented so that the wings flapped with a different frequency at different stages where each stage would be in the order of milliseconds, and [3] where additional weight and actuators were attached to construct a bulky body—we can easily acquire the tilt required to move in the $x - y$ plane by just attaching a small structure at the bottom containing a weight which is just moved around to apply torque and tilt the body by whichever amount and direction we need seamlessly and instantaneously, resulting in a compact mechanical structure, and a simple control system design.

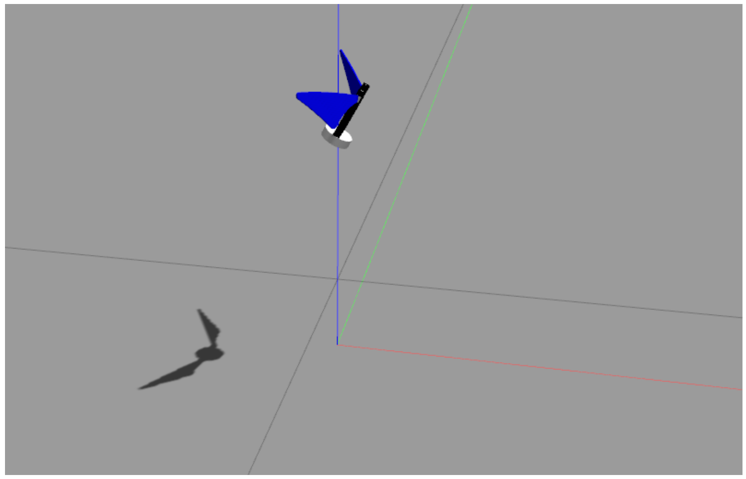

Fig. 10: Gazebo Image of the Beebot tilting forward

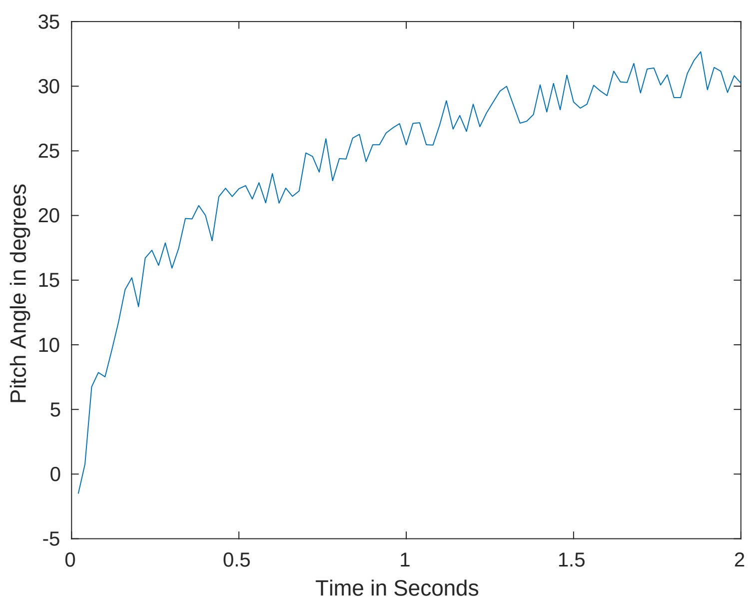

Fig. 11: Graph representing change in pitch of the Beebot as weight gets shifted

7 Conclusions and Future Work

We have proposed a light FWMAV for artificial pollination and validated it in simulation. The robot needs to be prototyped and tested for artificial pollination in real farms. Some of the challenges here would be controlling the yaw of the robot and making it resistant and stable to wind. Once its control system has been completely developed and power efficiency improved, it can easily and effectively be deployed in numerous applications such as not only artificial pollination, but also plant health monitoring, calculating crop yield, etc and also in other fields such as disaster management for locating survivors or monitoring and stealth uses for military purposes and so on. The MAV technology has innumerable amount of applications and can contribute to truly destructively effecting a lot of technological areas.

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