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A Novel Approach to Artificial Robotic Pollination through the Biomimicry of Bee Anatomy and Morphology

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Abstract

The aim of this project was to develop a robotic pollinator through the biomimicry of bee anatomy and morphology. Designs for the overall structure are provided; however, theprimary focus of the project was to develop the more specialised robotic pollinating limb. The investigation focused on honeybees of the species Apis cerana and bumblebees of the genus Bombus. Microscopic images of honeybee legs and hairs were analysed using algorithms, and their dimensions were determined. The results displayed a difference in dimensions, hair separation, hair length, and other parameters between the three types of legs,of which front legs were found to be best adapted for pollination. These results were used to develop a 3D computer-aided design of a robotic pollinator to effectively mimic honey bees. Additionally, an electronic circuit containing an electrostatic generator and vibration motor was created for the pollinating limb, mimicking the electrostatic attraction of pollen and the phenomenon of 'buzz pollination' used by bumblebees. The investigation also focused primarily on three plant species, Lagenaria siceraria (bottle-gourd), Solanum melongena(brinjal), and Luffa acutangula (ridge-gourd), analysing the dimensions of the pollen grains and the area they covered. Furthermore, a machine learning algorithm was trained to recognize flowers when present in an image and return their coordinates to guid the robotic arm, achieving a high accuracy and allowing for fully autonomous pollination. Finally, the design of the pollinator was created alongside an outline of its functioning. Such novel methods of solving the pollination crisis can prove invaluable in countering the decline in natural pollution and prove to be an important avenue for future research.

Keywords: artificial pollination, honey bees, biomimicry, machine learning, computer-aided design, classification, image processing, robotic pollinator design

Introduction

The process of natural pollination plays a critical role in sustaining human populations across the world, and the plant products of pollination are an integral part of the agricultural industryand global economy. 39 of the world's 57 most important monocultural crops depend on animal pollination, and 5-8% of all agricultural production directly results from it.[1] However, in light of recent declines in populations of natural pollinators due to a variety of reasons, natural pollination is growing increasingly threatened and can spell catastrophe if not tackled in a sustainable and feasible manner. Bee populations are not keeping pace with the 300% increase in demand for pollinator-dependent crops, and thus new solutions are required to ensure food security for the future.[2]

It is estimated that 87.5% of all flowering plants are pollinated by animals.[3] Honey bees, particularly the Western

honey bee *Apis mellifera* and Asian honey bee, *Apis cerana*, are the

most frequent floral visitors worldwide; *Apis mellifera*, for example, accounts for 13% of all floral visits, and 5% of species are exclusively pollinated by them. However, bee populations are on the decline, caused by a variety of interlinked factors. About 40% of all bee species arethreatened by extinction, as per the International Union for Conservation of Nature (IUCN), and in the United States, bee populations decreased by 40% in 2019.[4] Initially, decline was attributed to Colony Collapse Disorder (CCD), a phenomenon discovered in 2006 wherein worker bees abandon their hives, queen, and food supplies for unknown reasons. Recently, however, CCD cases have decreased in number, but a variety of other factors continues to impact pollinator populations. These include human actions like breaking of beehives; pests, like the parasitic *Varroa destructor* mite that feeds exclusively on honey bees; pathogens; poor nutrition caused by a loss of foraging habitat; exposure to pesticides and insecticides, particularly neonicotinoids; and a lack of genetic diversity caused by breeding techniques used in creation. Climate change has further complicated the equation, as changing weather patterns lead to a discrepancy between the blooming of flowers and the visits of pollinators, termed *phenological mismatch*. This decline in population and pollination is not limited to honey bees, but also bumblebees of genus *Bombus* and other pollinators, putting at risk pollination for a wide variety of important species.

This decline in natural pollination is greatly worrying, since 75% of the world's mainagricultural crops are partially dependent on pollination, along with other plant by-products that are essential for nutrition, medication, biofuels, wood, cotton, etc. Declining populations and pollination would result in a large blow to the agricultural industry and the economies of various nations reliant on the primary sector. However, current means of artificial pollination are time-consuming and require resources and manual labour, such as in hand pollination, or risk damaging the plant or denaturing pollen, as in spray pollination.[5] Thus, devising autonomous solutions for the same is important, in order to provide alternatives for beeswhen it is not possible to use them.

This research project thus aims to investigate two aspects: the process of pollination as facilitated by the legs; and the design of an artificial pollinator based on biomimicry of these properties to ensure accuracy and efficiency while avoiding the pitfalls of current artificial pollination methods.

Background Information

Pollination is carried out by the transfer of pollen from the stamen of a male flower to the stigma of a female flower for fertilisation. Natural pollination refers to pollination that occurswithout human interference. Various vectors of pollination can be responsible for this, such aswind, insects, animals, birds, or water. The main pollinators of plants are often animals, and pollination in this way is termed zoopollination. Honeybees perform more than 80% of the pollination of many cultivated crops, such as fruits like apples, mangoes, peaches, pears, oranges, raspberries, and watermelons. They also pollinate vegetables like pumpkins, bottle gourd, onion, carrot, cabbage, and many oil crops like sunflowers.[6] This makes them extremely important for the cultivation of several food crops consumed globally. Zoopollination by bees has several advantages over artificial pollination methods. As anatural process, it is free of cost and highly efficient since bees are specialised to obtain and transfer pollen. Bees also often rub against other bees that are working on different flower species in the hive, transferring pollen from one to another. This is valuable since it leads to cross-pollination, increasing the hybridization of plant species, increasing genetic variability, and therefore increasing the probability of survival of the plant. However, natural pollinators, especially

bees, are declining in population due to a variety of effects, which endangers both the species as well as plant species that rely upon it for pollination.

As a result of this decline in bee populations along with the consistently rising demand for agricultural products, artificial pollination methods have become an increasingly popular solution. They have several advantages over natural pollination methods and tend to provide higher conversion from flowers to export fruits. Unlike natural methods, artificial pollination is secure and stable because it does not depend upon any chance factors. This makes aspects such as the yield far more predictable for agricultural landowners. Furthermore, due to this control over the process, a large variety of hybrid plants can be produced by the use of artificial pollination. This type of pollination can also be used to acquire any specific characteristics that may be desired in a plant species (eg. resistance to disease or larger fruits) through artificial selection.[7] This refers to the identification of desirable characteristics in plants or animals by humans, and the actions taken to enhance and pass on such characteristics to the next generations.[8]

Unfortunately, present methods of artificial pollination face several limitations. Currently, themost commonly used methods involve (1) plucking male flowers and manually rubbing their stamen directly onto the stigma of female flowers, (2) rubbing cotton over the stamen to collect pollen grains and then shedding them over the stigma of a female flower, or (3) shaking the branches of self-pollinating plants to shed the pollen from the stamen to the stigma.[9] These are extremely time-consuming and labour-intensive which decreases the profitability of an agricultural business. Furthermore, the precise methods that must befollowed often require careful training of the staff working in the fields. Such manualpollination methods also generally have a lower rate of successful pollination, and most plants are pollinated by others of the same species that are located nearby to minimise manual labour, which leads to lower genetic diversity and lower hybridization.[10] Another artificial pollination method, termed spray pollination, involves spraying pollen grains onto the flowers. This has been found to give comparable results to hand pollination and requires less time and labour[11], but the pressure from the sprays may damage flowers, and this does not provide a solution to the collection of pollen, which is the primary step.

To generate a more effective approach to artificial pollination, it is important to consider the various characteristics of bees that make them specialised for this process and attempt to mimic these in whatever approach is chosen. Because they spend the majority of their lives gathering pollen, which is a source of protein that they give to their developing offspring, bees are great pollinators. Electrostatic forces are used by the hairs on a bee's body to draw pollen grains to it when it lands on a flower. As bees fly through the air, their bodies become positively charged with static electricity. As a result, when a bee lands on a flower and knocks some pollen from the delicate anthers, some of these pollen grains stick to the static-charged hair covering the bee's body. Through the use of the stiff hairs on their legs, bees then groom the pollen into specialised brushes or pockets on their legs or bodies andthen take it back to their nest. A given bee is likely to transmit pollen from one flower to another of the same species since bees prefer to concentrate on only one type of flower at a time. To generate healthy seeds, many plants require this kind of pollen distribution, known as cross-pollination.[12]

Another useful approach used by bumblebees, from the genus *Bombus*, is termed 'buzz pollination'. Numerous plant species have developed floral traits that restrict access to pollen.Buzz pollination is a method of pollination in which bees extract and collect pollen from flowers using vibrations. The vibrations draws the pollen out of the stamen, and in generalcan be used to dislodge pollen that is on the surface of the anther. This is attracted by thebees' positively charged bodies and then collected and stored in pollen baskets on the legs andbody.[13]

Figure 1: parts of the honeybee leg[14]

The morphology of the bee leg is also equally integral to its ability to extract and collect pollen. The shape and proportions of the various parts of the leg, such as the femur, metatarsus, and pretarsus, allow for bees to effectively rub against the anther and collect pollen from the stamen. Moreover, the hairs on the body and legs of honeybees, specifically *Apis cerana*, are integral to the collection of pollen and also its retention on the bee's body.[15] The spacing between bees' minute hairs permits them to gather large amounts of pollen and also to rapidly brush it off when visiting a new flower. *Apis cerana* are able to carry pollen equal to almost 30% of their body weight on the surface of their bodies.[16] They make use of their forelegs to remove these pollen grains when visiting new flowers. In an attempt to more closely study the impact that the morphology of the honeybee has on its ability to carrypollen, David Hu, from the Georgia Institute of Technology in Atlanta, and his colleagues found that the spaces between hairs on the bees' bodies are almost equal in width to the pollen grains that these bees typically collect. This allows for the particles to fit into the hairs and be easily dislodged. In comparison however, the hairs found on the bees' forelegs, which are used to collect the pollen, are positioned much closer together. This allows the pollen to be embedded in the hair, enabling large amounts of pollen to be removed with each leg swipe.The team also found that the pollen easily sticks to the hair, aided by the presence of the pollen kitt, a viscous liquid found on pollen surfaces.[17]

Methodology

In our project, dead specimens of *Apis cerana* worker bees were acquired from gardens around beehives and from beekeeping farms. These were carefully handled and dissected to separate the front, middle, and back legs from the body without damaging the limbs. The legswere photographed using a USB microscope camera (50x to 1000x) at varying degrees of magnification, and the height and width of the captured area were recorded in millimetres. The images were then processed through specifically coded algorithms implementing the OpenCV library in the

Python language. The total length of the bee legs, along with the lengths of individual sections, was calculated through manually plotting points on the image, utilising coordinates to calculate the distance between consecutive points, and scaling the values depending on the real size the image corresponded to.

Meanwhile, to calculate the angle between the joints, points were plotted as above and the angle computed through the *atan2()* function. Similar image processing was done for images of bee hair. These were magnified by 3x owing to their small size, in order to better pinpoint the hairs manually, and the distance between adjacent hairs was calculated. The process was repeated for the front, middle, and back legs for 5 bees, and the values averaged, and the standard deviation of the data calculated. The results derived from these were used in the formulation of parameters for our design.

Pollen grains were extracted from *Lagenaria siceraria*, *Solanum melongena*, and *Luffa acutangula* through swabbing the stamen of the same, and pictures were taken. The contoursof pollen grains were determined through using the OpenCV *contours()* function after determining the necessary HSV values for the lower and upper bound masks. Using the contours, the area of the pollen grains was found, and a bounding rectangle created around individual pollen grains in order to determine their shapes and dimensions.

Furthermore, building upon the information that electrostatic attraction plays a role in natural pollination, an electronic circuit was developed to induce a static charge in a metal plate. Alongside this, a vibrational motor was incorporated in the circuit to mimic buzz pollination, performed by bumblebees for certain types of plants. The circuit was tested on pollenextracted from *Lilium candidum* flowers, owing to their relative availability and similarity in size and features to the pollen of the aforementioned species. The voltage required for the circuit was determined based on the ability to attract and retain pollen when the ion generator was running. A machine learning algorithm was also developed to recognize flowers, based on the YOLOv5 architecture. Initially created on a database containing a variety of flowers and solely recognizing whether a flower was present, a new algorithm was created that classified the flowers into specific species, trained on a dataset of *Lagenaria siceraria*,*Solanum melongena*, and *Luffa acutangula* flowers.

Algorithm

Images were processed through placing points on an interactive window that denoted the locations of leg joints, following which the algorithm calculated the distance in pixels between subsequently placed points, as well as the angle formed between three subsequent points, printing the values of the same. Angles were calculated using the atan2 function for maximum convenience and accuracy. A similar algorithm was utilised for analysing images of bee leg hairs, but owing to their small sizes, manually placing points was prone to error. Thus, images were enlarged by 3x and then the same process was carried out, with the values for calculated distance being appropriately scaled. For pollen grains, hue saturation value (HSV) parameters were determined through using a specific program to generate the optimum mask, and these values were accordingly used to determine the contours of pollen grains through the OpenCV function provided. A bounding rectangle was then created aroundthe contours detected, in order to find the lengths of the diameter and axes, depending on whether the pollen was elliptical or circular in shape. The surface area of the pollen grainswas thus estimated through using the above values. Images below display snapshots of the code used for image processing the data. These algorithms were

developed in Python, utilising the OpenCV library to load images and determine key characteristics of theirs.

Apart from image processing, a machine learning algorithm was developed that used the YOLOv5 architecture to accurately identify whether a flower was located in an image, and return the coordinates of the bounding rectangle that encompassed the flower's location. YOLOv5 is a novel convolutional neural network (CNN) that processes the entire picture, then separates it into parts and predicts bounding boxes and probabilities for each component.It can detect objects in real time and with great accuracy.

We used a pre-trained model of the YOLOv5 Object Detection Algorithm on 2 datasets: primary data on bottle-gourd, ridge-gourd, and brinjal flowers, and secondary data from google's open image dataset for general flower detection. The primary dataset was annotated using Roboflow and augmented to adjust for exposure and saturation. This resulted in a dataset with 500 images and over 1000 instances of the required flowers. The secondary dataset consisted of 2048 images and over 5000 instances of flowers. The final size of the images used was 640 pixels, and the batch size was 8. The primary model ran for 20 epochs before overfitting, and it finally yielded a mean average precision (mAP) of 0.85 while the more generalised flower detection model yielded a mAP of 0.73.

Figure 2: machine learning algorithm detecting flowers in images

Results

The values found for the measurement of each leg of the bees investigated are detailed below in Tables 1, 2, and 3. The legs were found to be multi-jointed structures, with each leg having6 distinct parts; the parts were numbered beginning from that closest to the body, the coxa, and proceeding all the way till the tarsomeres.

Fig 3a: front leg *Fig 3b: middle leg* *Fig 3c: back leg*

Figure 3: sample image processing of bee no. 1

Table 1

Bee No.	Length of front leg segment no. / mm						Total length / mm
	1	2	3	4	5	6	
1	0.56	1.23	1.55	1.98	1.53	0.88	7.71
2	0.52	1.22	1.53	1.97	1.54	0.86	7.64
3	0.55	1.26	1.54	2.00	1.55	0.85	7.75
4	0.53	1.24	1.54	1.99	1.54	0.86	7.70
5	0.51	1.23	1.52	1.98	1.52	0.84	7.60

Bee No.	Length of middle leg segment no. / mm						Total length / mm
	1	2	3	4	5	6	
1	1.44	1.66	1.90	1.61	2.12	1.43	10.16
2	1.43	1.64	1.87	1.60	2.11	1.41	10.06
3	1.45	1.65	1.91	1.62	2.14	1.42	10.19
4	1.44	1.67	1.88	1.62	2.13	1.44	10.18
5	1.42	1.63	1.86	1.58	2.09	1.38	9.96

Table 2

Bee No.	Length of back leg segment no. / mm						Total length / mm
	1	2	3	4	5	6	
1	0.72	2.74	3.44	2.38	0.90	1.07	11.26
2	0.71	2.72	3.41	2.37	0.91	1.05	11.17
3	0.74	2.75	3.47	2.40	0.91	1.08	11.35
4	0.73	2.74	3.45	2.39	0.92	1.07	11.30
5	0.70	2.71	3.39	2.38	0.90	1.06	11.14

Table 3

Leg type	Average length of segment / mm						
	1	2	3	4	5	6	Total
Front	0.53	1.23	1.54	1.98	1.54	0.86	7.68
Middle	1.44	1.65	1.89	1.60	2.11	1.42	10.11
Back	0.72	2.73	3.43	2.38	0.91	1.07	11.24

Table 4

Front and middle legs had a hook-like structure, whereas back legs had an L-shaped structure,as displayed in Figures 1a, 1b, and 1c. Front legs had a more acute central angle and thus a more noticeable hook. The values for the angles of individual joints is displayed on the images themselves, corresponding to the location of the angle. These angles were further investigated to determine the degrees of freedom that bee legs had, particularly in dictatingthe length of the leg when unbent and fully extended, and the approximate dimensions of the leg when each joint is fully bent. Front legs were found to fit in a 4 x 2 mm area, middle legs in 3 x 2.5 mm, and back legs in 6 x 3 mm.

The separation between hairs of each of the bee legs was also similarly analysed, for each leg on each bee separately. The values displayed are averages taken of the values found for separations on each bee. These results are detailed below in Table 5, along with its standard deviation.

Bee No.	Separation between hairs / mm		
	Front Leg	Middle Leg	Back Leg
1	0.0275	0.0411	0.0503
2	0.0287	0.0426	0.0512
3	0.0264	0.0401	0.0499
4	0.0312	0.0435	0.0524
5	0.0291	0.0429	0.0518
Avg.	0.0286 ± 0.0018	0.0420 ± 0.0014	0.0511 ± 0.0009

Table 5

Figure 4: images of honeybee back, middle, and front-leg hairs (clockwise from top left)

Pollen grains of *Lagenaria siceraria*, *Solanum melongena*, and *Luffa acutangula* were also investigated through image processing. The area and dimensions of individual grains of pollen was calculated and results are detailed in Table 6.

Species	Area / mm^2	Shape	Axes dimensions / mm
Lagenaria siceraria	0.005	Round	0.1 x 0.1
Solanum melongena	0.001	Elliptical	0.03 x 0.05
Luffa acutangula	0.026	Elliptical	0.26 x 0.15

Table 6

While there is variation amidst the sizes of the pollen grains, they are all greater in diameter than the separation between bee hairs, which is an important characteristic to maintain. If pollen grains were smaller than the separation, they would simply not stick on the hairs but rather fall within gaps and be unable to be extracted. However, if the hair density would be too high, there would be no free space to house the pollen grains. Achieving a balance between the two is critical for the design of an artificial pollinator.[18]

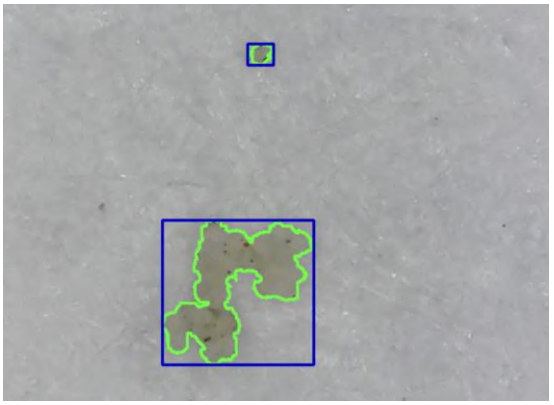

Fig 5a: Lagenaria siceraria

Fig 5b: Luffa acutangular

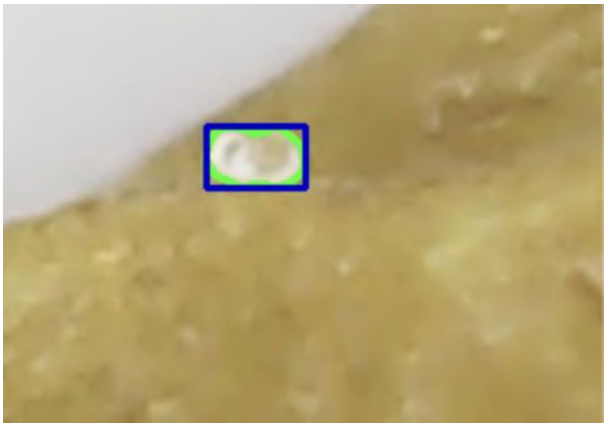

Fig 5c: Solanum melongena

Figure 5: images of pollen extracted from specific flowers

The results detailed so far display that each leg of a honey bee has unique dimensions and properties that are tailored for specific purposes. The front leg, in particular, possesses an acute angle, high hair density and low

separation between hairs, and a relatively thin leg, which results in it being well adapted for gathering pollen from flower stamens. The middle leg also achieves this aim, with similar characteristics. The back legs, with their thickness andshort, comb-like hairs, are more suited for providing support when bees land on flowers, and gathering pollen attached to the other legs, to be collected in specific structures called pollen baskets. Thus, in developing a design for an artificial pollinator, it is the parameters of the front leg that are most valuable to us, since it is most significantly involved in the process of collecting pollen.

Concept

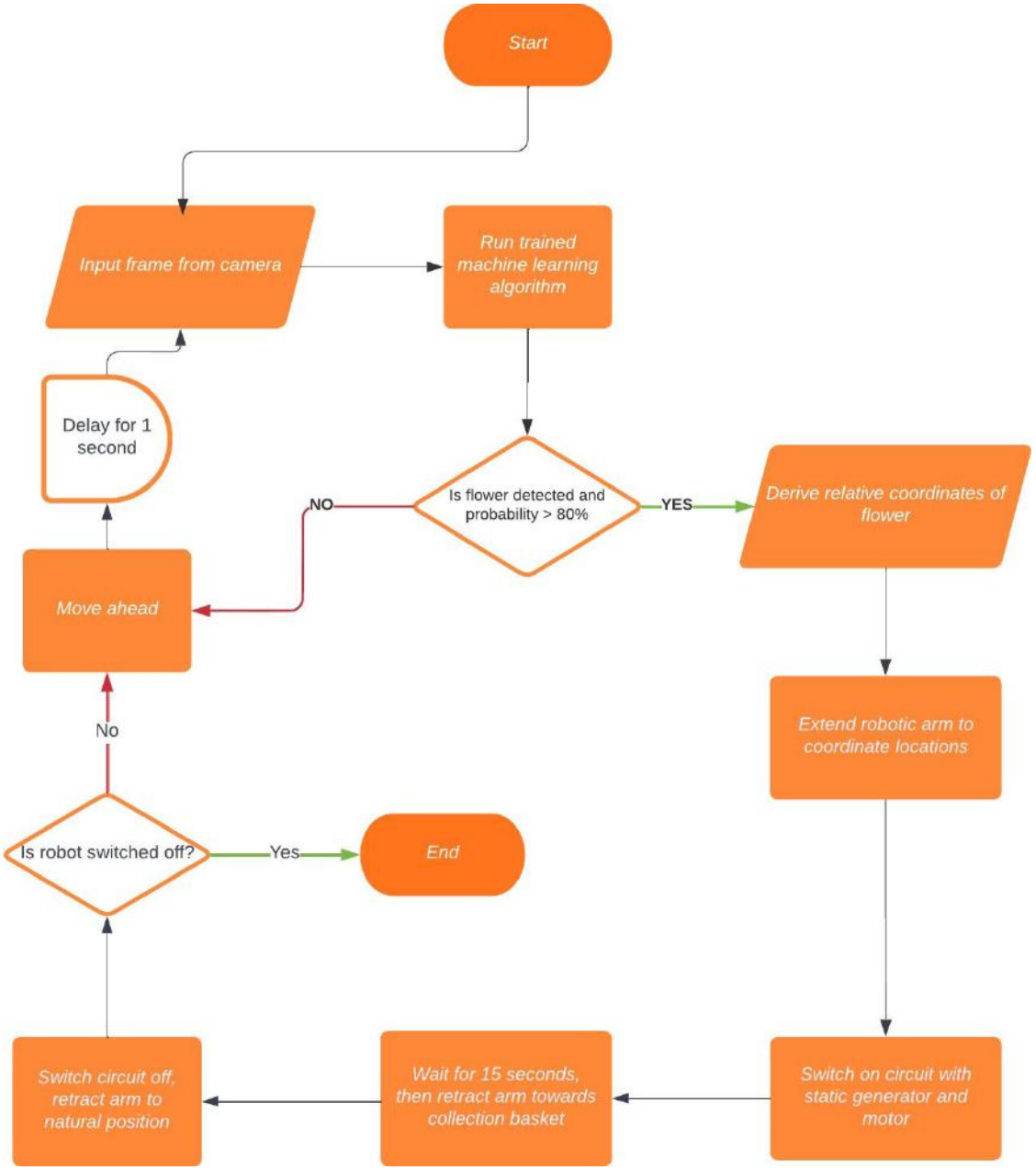

Figure 6: algorithm for pollinator functioning

The initial conception of the artificial pollinator was designed to autonomously conduct gathering and collection of pollen, through employing a camera with a constant video feed, wherein the frames would be processed through a machine learning algorithm. Depending on whether a flower was detected in the image or not and if its probability (returned by the algorithm) was sufficiently high, the relative coordinates of the flower would be obtained from the image and a robotic arm would be accordingly moved towards the location of the flower. Then, a circuit would be switched on, where a rotational motor would dislodge pollenfrom stamen and an electrostatic generator would attract the pollen. After 15 seconds, the armwould retract to a collection basket, the circuit would switch off (thereby dropping the pollen into the basket), and the arm would return to its starting position. The robot would then move forward and the process would repeat.

Circuit Design

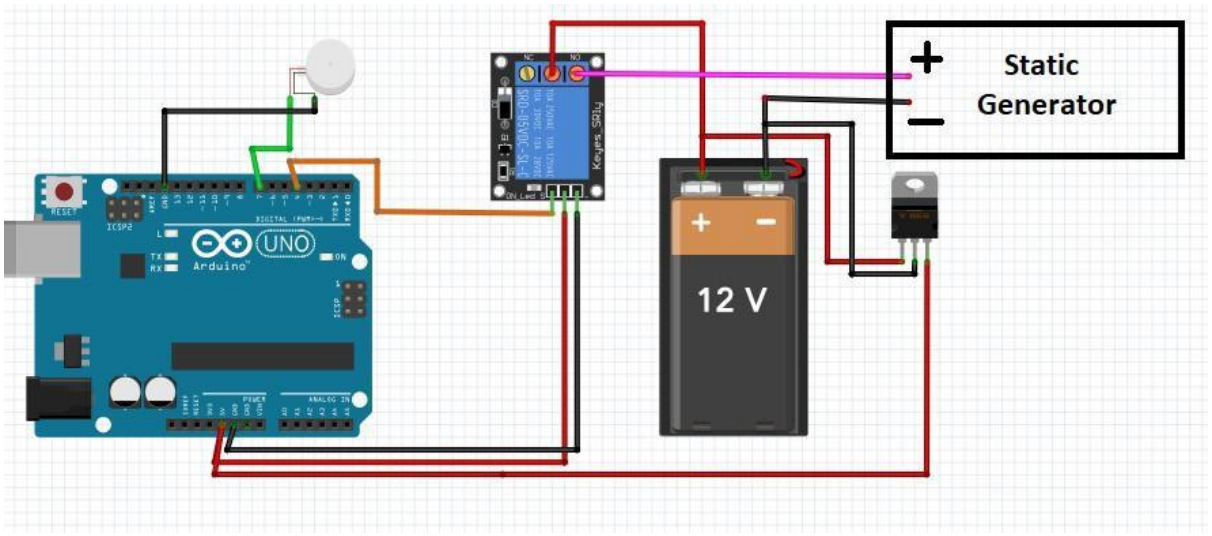

Figure 7: simplified circuit design displaying main pollinator functions

This circuit involved a vibration motor and an electrostatic generator powered by a 12V battery and controlled using an Arduino UNO board. This aimed to mimic the concept of 'buzz pollination', using the vibration motor to dislodge pollen from the flower's stamen. The electrostatic generator would then attract the pollen grains, mimicking the ionically charged body of a bee.

In order to test the optimal voltage of the battery being used in the circuit, an investigation was carried out. A potentiometer was then added to the circuit to vary the voltage. 1 gram of pollen was manually extracted from *Lilium candidum* flower anthers, and a metallic plate attached to the electrostatic generator was held at a distance of roughly 5mm from the pollen grains. The amount of pollen attracted to the plate was collected separately and weighed. The results of the investigation are summarised below.

```
int vibrationMotor = 7;
int staticGenerator = 8;

void setup() {
  pinMode(vibrationMotor, OUTPUT);
  pinMode(staticGenerator, OUTPUT);
  digitalWrite(staticGenerator, HIGH);
}

void loop() {
  digitalWrite(vibrationMotor, HIGH);
  delay(1000);
  digitalWrite(vibrationMotor, LOW);
  delay(1000);
}
```

Figure 8: Arduino code

Voltage / V	Percentage of pollen attracted / %
0	0
1	0
2	0
3	0
4	0
5	7
6	19
7	31
8	43
9	52
10	61
11	67
12	72
13	74
14	74
15	75

Table 7: voltage vs pollen attracted

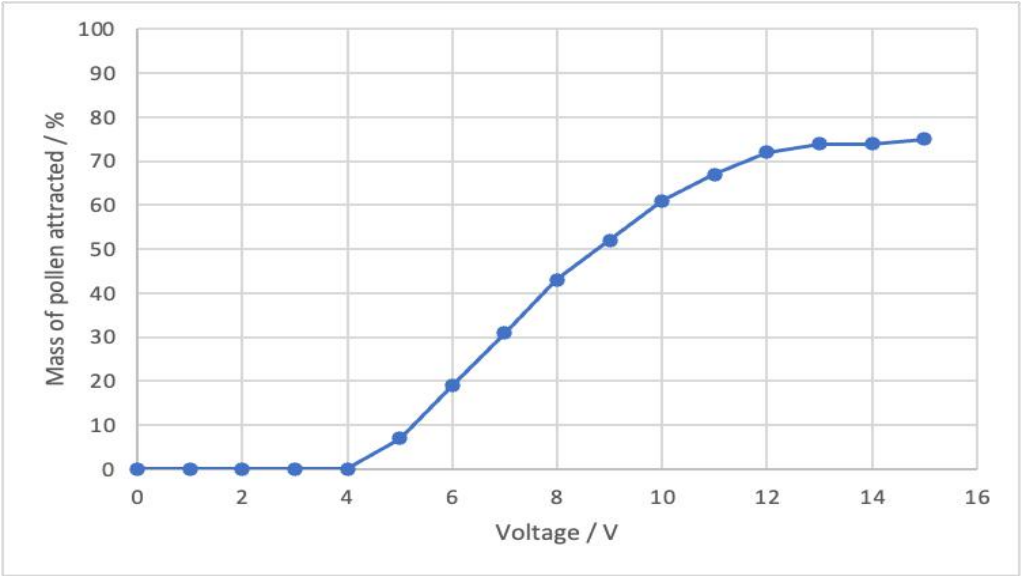

Figure 9: graph of voltage vs percentage of pollen attracted

The increase in the mass of pollen attracted reduced with every unit increase in the voltage,plateauing at 15V with 75% of the pollen grains attracted. However, with an almost negligible increase beyond 12V (72% pollen attracted), the pollinator featured a circuit of

12V to maximise the efficiency while simultaneously minimising the cost of production. Furthermore, 12V batteries are easily available and thus the decision to have the circuit runon 12V is based on practicality as well.

Parameters for Design and CAD Model

The overall design for the artificial pollinator was based on the parameters determined in the Results section outlined above. The pollinator would consist of a retractable circular robotic arm, to which twelve legs would be attached at an angle of 30° to each other. The parameters of the leg would be based on that of the front leg of the bee, as displayed below.

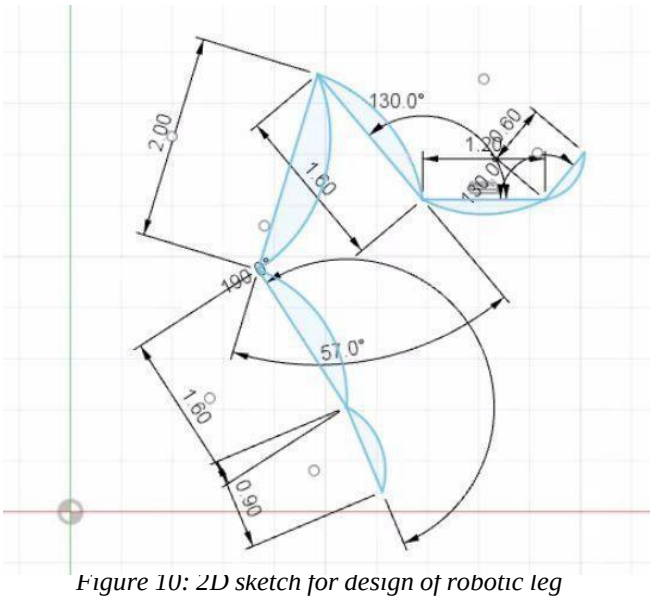

Figure 10: 2D sketch for design of robotic leg

This robotic arm would be made of lightweight silicon with a rough, sticky texture, and minute projections in order to maximise the area of the leg and the chanceto retain pollen. Synthetic hairs would be attached to the same. The angle between joints and the degrees of freedom were alsodetermined based on the information highlighted above, as was the width of the legs.

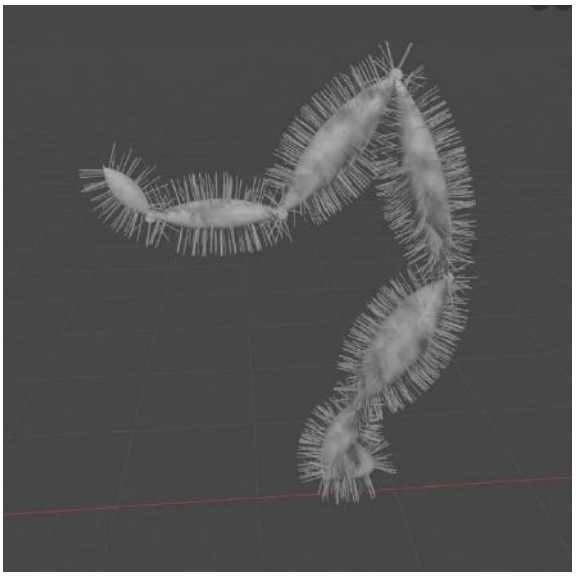

Figure 11: Single robotic leg

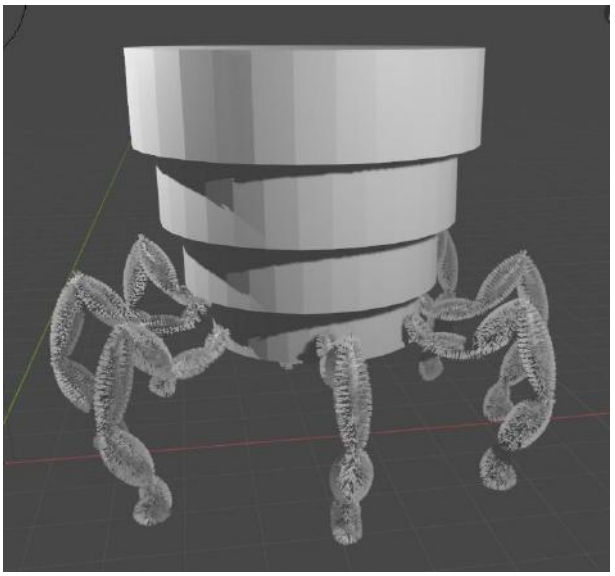

Figure 11: Tip of robotic arm with 12 legs attached

Parameters for Design:

Robot dimensions	3 x 2 x 2 feet
No. of robotic bee legs	12
Total unfolded length	7.9 mm
Width of robotic bee-legs	1 mm
Gap between hairs	0.04 mm
Electrostatic circuit voltage	12V
Motor speed	60 RPM
Hair width	0.01 mm
Material of hair	lightweight silicon

Incorporating the circuit described above, the motor intended to mimic buzz pollination would be housed within the main robotic arm and not the legs; when rotating, it would cause the arm to move up and down slightly, thus causing the legs to brush against the stamen ofthe flower. The static electricity generator would serve as the main method of collecting pollen, alongside any pollen that would get attached to the legs.

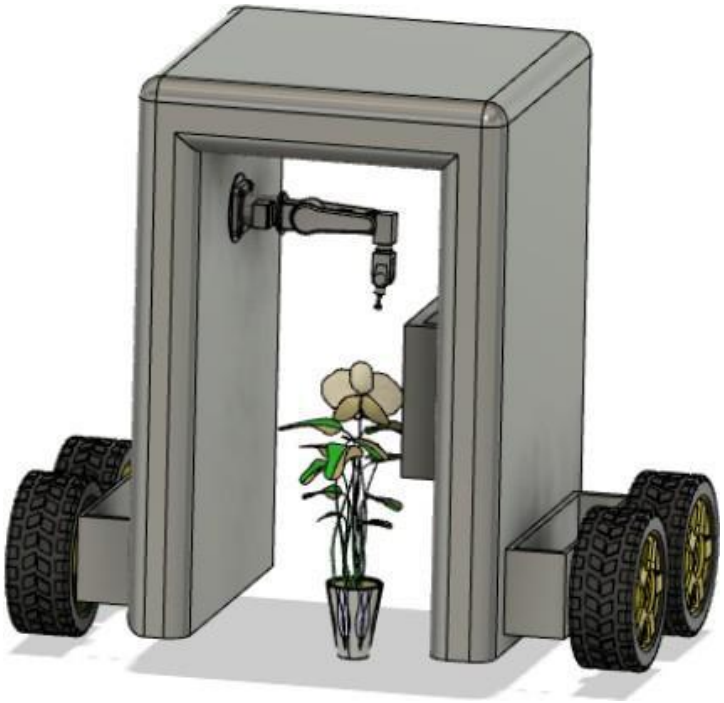

Figure 12: pollinator design

This arm would be connected to a robotic structure that travels on the ground, rather than being piloted by a drone. A basket would be attached to this structure where the attracted pollen is deposited through switching the circuit off and thus stopping the electrostatic force. This design eliminates the drawbacks of pollination through drones, namely the need for a human pilot to guide the drone and the possible damage to plants due to the air currents and pressure from the drone's engines. Furthermore, since the robotic arm extends towards the flower, it does not rest upon it, exerting no weight, similar to the average weight of 0.1-0.2g of a worker bee. As the robotic pollinator is designed for agricultural purposes, where flower plants are grown in roughly linear plots, such a design would be optimal for artificialpollination.

Conclusion

Conducting extensive analysis of the dimensions of bee legs and hairs, the various properties of bees were quantified and accordingly used to create a computer-aided design of a pollinator. Furthermore, in order to mimic the feature of electrostatic attraction that bees utilise in pollen collection, as well as buzz pollination that is orchestrated by bumblebees, an electronic circuit with a vibration motor and static electricity generator was designed, tested, and implemented. Machine learning can also be effectively utilised to dictate the behaviour ofthe artificial pollinator, to determine whether a flower was detected in an image or not, and accordingly find its coordinates and extract pollen from it. Such methods could have wide-spread implications for artificial pollination; while the current prototype has been developed specifically for agricultural means, where flowers are of the same species and planted in a more regular manner, research is currently being conducted into determining species of flowers through machine learning and implementing this for a pollinator with more diverse capabilities. The increasingly vital role that natural pollinators (honeybees and bumblebees the foremost amongst them) play has

been accompanied by a decrease in their populations and an inability to keep pace with increasing demands for food and plant products. In light of this phenomenon, alongside conservation efforts, devising artificialsolutions is critical. Using biomimicry through mimicking the morphological structure ofbees can be a rewarding and particularly lucrative avenue to resolving concerns over pollination, especially for the agricultural industry.

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