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Design and development of honey bee inspired flapping mechanism for bio-inspired micro air vehicle (MAV)

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***Abstract*---**Over the last two decades, research on the miniaturization of unmanned air vehicles has accelerated exponentially, leading to the evolution of successive generations known as Micro Air Vehicles (MAV) and Nano Air Vehicles (NAV). In view of potential applications where human reach is inaccessible, multiple MAV ideas have been proposed such as fixed wing, flapping wing, and rotary wing. To develop a MAV flight mechanism, researchers idolize biological fliers such as birds and insects. Additionally, a researcher's knowledge of flight biomechanics and aerodynamic fundamentals is essential for assessing design parameters. The present study addresses a brief chronological review of many types of MAVs that have been developed thus far in conjunction with highlighting of numerous bioinspired fliers incorporated in the development of MAVs. In addition, several mechanisms of Flapping Wing MAV are discussed. An inspiration derived from a particular species of honeybee, namely *Apis Melifera* is utilized to develop an appropriate flapping mechanism taking into consideration the kinematic stability and aerodynamic features. Also, the concerns and challenges during early phase of designing the mechanism and scope of further research are discussed.

***Keywords*---**micro air vehicle, biomechanics, Apis melifera, flapping mechanism, aerodynamic characteristics.

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Introduction

Flapping can be seen as one of the most graceful and coordinated musculoskeletal locomotion present in nature. The simplest but effective kind of flapping mechanism can be seen in branches of tress during a powerful blow of wind such as hurricanes and tornado. But the flapping is disoriented and in random direction. The complexity of flapping can be seen in birds and insects. The physics of flapping have always fascinated biologists, physicists which has led to achieve an important milestone in the domain of bio-engineering namely Unmanned Air Vehicles (UAV). The actual history of UAV dates back to age of renaissance. The great polymathic Leonardo da Vinci was the first one to introduce the notion of MAV. But the pathbreaking moment in the history came in 1903 when Wright Brothers developed & tested first unmanned aircraft. The military application began in 1917 during World War II. The time period elapsed till today lead to crafting of several shapes and configurations accompanied by synonyms such as drones, flying robots, MAV, Nano Air Vehicle (NAV) etc. Subsequently with the advancement in technology, development of miniaturization of unmanned air vehicle was undertaken. The dimensions of MAV lie within the range of 15cm and possess weight around 10g. MAVs which derive inspiration from bird and insects are known to be as ornithopters and entomopters respectively. Based on the number of wings involved in flight bio-mechanics, insects may be classified as *Diptera* (two wings such as house flies) or *Hymenoptera* (four wings such as honeybee, fruit fly, bumble bee etc.). There are mainly two types of uncertainties involved any insect flight mechanism namely unsteady kinematics and generation of unsteady forces [1]. MAVs provides services in various domains such as military, civilian and metrology. In recent years, the multimodal robots have garnered significant attention in agriculture as well and could be a boon for country such as India which is primarily an agricultural economy.

Micro air vehicle (MAV)

Historical Evolution

The United Kingdom Department of Defence (DoD) defines MAV as a remotely operated multimodal robotic vehicle eliminating any aid of human operator comprising necessary electromechanical driving systems and may carry lethal and non-lethal payload [3]. In 1849, a researcher named Sir George Caley performed an experiment of glider carrying a boy. Due to his continuous research efforts and relevant publications earned him the status of “Father of Aeronautics”. Within 22 years of span, two new types of model airplanes were built on different powered mode namely clockwork powered (1854) and powered pusher-propeller (1871). In Late 19th century a Siberian based genius named Nicola Tesla gave demonstration of controlling of a boat just by using radio frequencies. During the same period, Louis Brennan too demonstrated wire guiding torpedo. Such demonstrations made scientists to ponder about development of UAVs for military purposes. In 1918, Curtiss Aeroplane and Motor Company jointly developed first plane for US Navy which featured self-navigation capability omitting the need an on-board person [2]. During 1947, research was heavily focused on developing radio-controlled aeroplanes and several improvements took place till 1970. But the real interest in developing UAVs because the researchers in US Department of Defence (DoD) thought of applying concept of miniaturization of radio modeled aeroplanes which can perform several military surveillance missions. Simultaneously, another agency named Naval Research Laboratory (NRL) too was pivotal in developing the first of a kind of MAV called Long Duration Expendable Decoy (LODED). Although it failed in the given mission, but it provided valuable research informations about the technological constraints needed to be overcome. Further NRL developed around 50 different models of UAVs and performed wind tunnel tests. Based on the results, it was evident that aerodynamic stability, airframe structure and low Reynold's number must be considered for designing. In December 1992, RAND Corporation conducted feasibility studies on MAVs and predicted that in the next ten years of span it would be possible to develop fully autonomous robotic air vehicles owing to the pace of development in micro-mechanical systems. Since then, there have been numerous MAVs developed. Currently, nano miniaturization had given birth to other class known as Nano Air Vehicles (NAV)

Types of MAVs
Fixed Wing MAV

Fixed wing MAVs are aeroplane modeled to suitable scale coupled with non-movable wings. Fixed wings MAV generates only lift and propeller-based mechanism is incorporated to generate thrust [4]. The first of its kind was Black Widow (fig.1) developed by Defence Advanced Research Projects Agency (DARPA). Wood et. al developed a palm size comparable glider and demonstrated at Harvard University [5]. It has been pointed that in designing the airfoil the lift to drag ratio plays an important parametrization. Designing of MAVs have always posed a challenge for materials scientists. Various researchers did put effort in researching possible areas of reducing structural weight. Lian et al. [6] developed a 6-inch bio-inspired MAV by selecting carbon fiber for skeleton, rubber for wing membrane and carbon fibre prepeg cloth for fuselage which helped achieving final weight of MAV within the range of 55 gms. E. O'Keefe et.al [7] identified micro-foamed polymer composites and metal oxides as the potential materials possess sufficient strength modulus as well as excellent assemblage capabilities. In University of Florida Martin R. Waszak and John B. Davidson [8] fabricated truss shaped fuselage of carbon fiber and epoxy material (fig 2).

Fig 1. Black Widow MAV

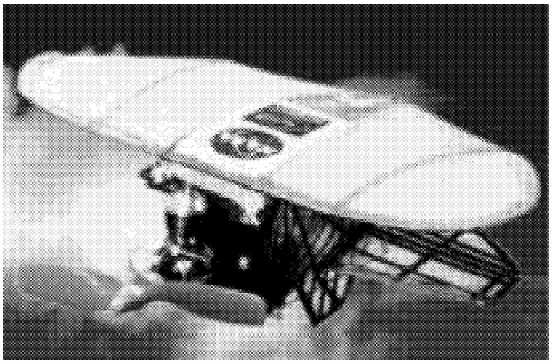

Fig 2. MAV Developed at University of Florida

Chinnapat Thipyopas et. al combined the concept of fixed wing VTOL (Vertical Takeoff and Landing) airplane and counter direction rotors which provides an additional degree of freedom (DOF) in yaw axis [9]. On the basis of wing geometry, fixed wing MAVs can be classified as conventional wing, canard wing, box shape wings, trapezoidal wings etc [3]. Based on type of engine installed; turbojet engines for high speed and piston engine along with propellers for subsonic range. Based on the shape of tail; H shape, or V shape etc.

Rotory Wing MAV

Rotary-wing MAVs are those which generates the thrust and lift by using multi propeller systems mounted on them. There are two main categories; cyclogyros and autogyros (fig 3). In cyclogyro system, the blades mounted on hast rotates along a horizontal axis as well as parallel to it as well. On the contrary, autogyro system employs dual rotors. One unpowered to generate lift and another engine powered to provide thrust [3]. Multirotors are further classified on the basis of number of propellers such as tricopters, quadcopters, hexacopters and octacopters. As compared to fixed wing MAVs, rotary wings possess higher weight and offers less less endurance and speed [4]. Also, rotary wings require large space for operation owing to geometrical configuration.

Fig 3. A Cyclogro System (left) & Autogyro Sytem (Right)

Application domain of Rotary MAVs are military warfare, agricultural monitoring as well groceries delivery. Research has been done in the direction of further miniaturization. Bohorquez et al. from University of Maryland developed co-axial rotor system named MICOR and was tested for thrust and power [10]. During flight test, the MAV was self-powered and a flight time of 3 minutes was achieved.

Another team of researchers, Vikram Hrishikeshavan et al. from the same university developed dual blade shrouded rotor (rotor surrounded by a cylindrical duct) MAV of around 250 gms showcasing superlative hovering efficiency and payload capacity. Incorporation of higher number of rotors simply means higher lift and power generation but at the same time large weight. While comparing to fixed wing and flapping wing systems, a relatively less research has been conducted in rotary ones. Several rotary systems are shown based on the no of rotors.

Fig 4. (a) Monorotor (b) Birotor (c) Trirotor
(d) Quadrotor (e) Pentarotor (f) Hexarotor

Flapping Wing MAV (FMAV)

It is a very interesting genre and highly researched domain of all the other MAVs. FMAVs are based on bio-inspirations such as birds and insects and hence are also known as Biomimetic Mirco Air Vehicles (BMAV). The thrust and lift generation are made possible by periodic and continuous flapping action of wings. To achieve desired flight characteristics, the main parameters considered are geometrical contour of flapping wing, low Reynold's Number and wing flapping frequency. Comparatively FMAV generates thrust of higher magnitude compared to fixed wing counterpart. There are mainly two kinds; Entomopter and ornithopter. The former draws inspiration from insects a while the latter from birds. However, even after substantial amount of research, there are certain areas that possess challenges such as aerodynamic stability, payload weight, designing of wing profile and the weight of electronic configuration. The first and the foremost novel approach of FMAV is "Biomimetic is always a good point to start with" which means that as compare to man-made robots, natural flyers possess superlative capability to overcome various dynamic factors such as high gust of wind, temperature etc. Therefore, it is not only the bioinspiration but also one must have knowledge how the natural flyers overcome such situations [12]. As flapping is a complex mechanism to replicate which leads to difficulty in flight control as well as in fabrication of the components. The essential feature of a FMAV is the integrity of lightweight structural materials, miniaturized driving mechanism and internal electronic subsystem and has posed challenges since from decades. Adam Cox et. al [13] developed an unimorphic and flexure based four bar and five bar linkage piezoelectric mechanisms and conducted experimental studies on mapping of performances. The wings were fabricated from carbon fibre and the whole MAV weighed around 23g. Madangopal et al. [14] developed an entomopter inspired from the fact that an insect's thorax serves as a storehouse for reserving a fraction of kinetic energy as elastic potential energy. The authors incorporated a four-bar spring mechanism. The tension in the springs ensures that torque levels are in accordance with those of driving motors. A T Conn et.al [15] presented a classification of the flapping mechanisms. A MAV was developed in of parallel crank-rocker mechanism and was tested for effects of wing kinematics on aerodynamic parameters. Apart from a flapping mechanism, MAVs require high powered actuators as well which serves as driving force. Considering low weight requirement, selection of suitable actuators is also a challenging task. Michael Karpelson et al. [16] presented a comprehensive review of potential actuators and electronic equipment that can be used in MAVs. An actuator force is proportional to various parameters such as driving mechanism, wing geometry and no of stages in transmitting power. The actuators may be classified in two categories; Shape memory actuators and piezoelectric actuators. The former requires high current but low voltage for operation while the latter is known for its voltage-based operation i.e., high voltage but low current. Around 10% of total weight is dedicated for sensors and actuators and the remaining for structural materials. The total weight of a MAV decides the total flight time of the same. In-case the total weight of structural material and mechanism exceeds its predetermined range, the battery capacity is calculated based on the remaining weight. Some MAVs have been designed based on insects possessing four wings. Bolsman et.al [17] developed a four wing MAV using the structural materials namely carbon rods, mylar sheets and spring steel as a flexible member facilitating passive wing rotational motion. In addition, a ring structure analogous to flywheel had been introduced for energy storage purpose integrated with acquiescent mechanism for the very purpose of motion amplification. The amplification so generated to achieve a substantial amount of lift. Over a period of time piezoelectric actuators have gained popularity. Shijun Guo et.al [18] introduced the concept of a flapping wing rotor for MAV consisted of piezoelectric actuator and the aerodynamic efficiency had been tested through FEM and CFD analysis. The author pointed that an introduction of motion amplifier will further increase the amount of lift. Dr. Rajashekar Patil et al. [19] designed and developed a rubber band powered ornithopter and used tissue paper, balsa wood and acrylonitrile butadiene styrene (ABS). The author demonstrated the superiority of rapid prototyping as best choice of manufacturing technique which resulted in less weight structural parts in addition to improvement in strength.

Present work

Bioinspiration

In present study, honeybee serves as a source of bio-inspiration. A particular species of honey bee namely Apis Mellifera (shown in fig 5) also known as European Honey Bee is selected due to its abundant availability in Karnataka State of India. In fact, these species can be found almost everywhere on entire plant except Antarctica.

Fig 5. Apis Mellifera; Top view, Left-Side & Right-Side View

Apis Mellifera is divided mainly into four classes; queen bee, drone bees (male), worker bees(female), nurse bees. The major difference between drone and worker class is the absence of strings in former. A complete lifecycle consists of four distinct stages; egg, larva, pupa and finally adult. Worker bees are involved in the construction, maintenance and protection of honeycombs. The queen bee lays eggs in each of hexagonally combs which are nurtured by nurse bees.

A honeybee consists of two pair of wings namely forewing and hindwing (one pair each) When a honeybee flaps its wings, three distinct movements can be observed: sweeping or flapping, heaving (up and down movement) and pitching (changing incidence angle). In fig. 6, a honeybee's left-wing action is depicted in a schematic form. The wing motion consists of two translations (a downstroke and an upstroke) and two rotations in one complete flap cycle (termed pronation at the end of the down-stroke and supination at the end of the up-stroke). Additionally, the wing pitches rapidly at the conclusion of a half-stroke during rotation (stroke reversal). Depending on the insect and the flight motion, the wing kinematics might be rather variable. It's possible for insects to alter their flight path by altering their stroke angle, attack angle, and wing rotation. Flying insects have piqued the curiosity of biologists and engineers alike, as normal aerodynamics theory would seem to rule out such a feat. Insect flight aerodynamics are incomprehensible because of their small size, high stroke frequency, and unique reciprocal flapping motion. Although high-speed video, new methodologies like digital particle image velocimetry (DPIV), and fast computers for simulation and analysis have considerably benefited researchers, there is still much work to be done. Insect flight aerodynamics has made great progress thanks to our improved understanding of kinematics, forces, and flows.

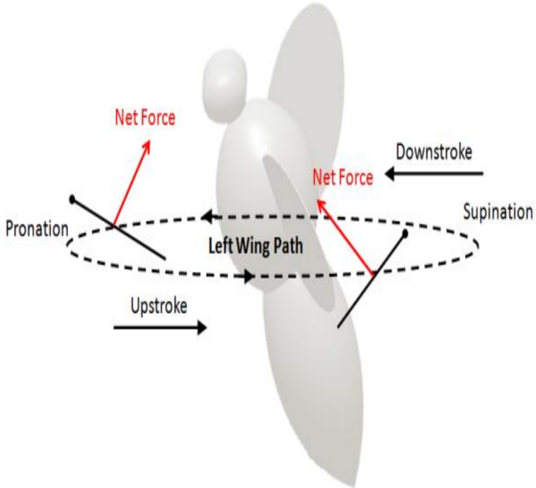

Fig 6. Depiction of flapping wing action of a honey bee

In present study, Apis Mellifera species is taken as a source to replicate biomimicking of flapping mechanism. From numerous literatures referred, it is evident that study of bio-inspiration by considering honeybees constituents mere 2% of all the bio-inspirations developed so far. Hence

Software Utilized

The present work employs SolidWorks to design and develop a 3D modelling of honey bee inspired flapping mechanism. E Salami et.al [20] developed dragonfly inspired wings employing SolidWorks as Computer Aided Design (CAD) software and later on was converted into a compatible format for a 3D printer. Four bar linkage (FBL) is widely used flapping mechanism. Lung-Jieh Yang [21] fabricated a 20 cm MAV named "Golden Snitch". The linkages of the mechanism were designed by SolidWorks software and simulations were carried out assuming the rigidity of linkages. However, in reality the flapping angle exceeded by 12^0 owing to the bending characteristics of carbon fiber. The CAD design and simulation of SolidWorks is also extended in designing rotary MAVs. Mohammad Shaqura et.al. [22] designed, assembled and simulated and also used for model validation. SolidWorks provides engineered Application Program Interface (API) in which a user can feed important informations such as airframe structure coordinates, wing topology, material properties etc. The user interface is easy to use and hence the main reason to use a SolidWorks a preferable CAD software. In addition, the software also provides a good approximation for Centre of Gravity (COG) which is one of the main parameters while fabricating and assemblage of parts. Matt McDonald et.al. [23] developed an idea of spherical four bar linkage flapping mechanism. The researchers developed a 3D model of the same by using SolidWorks. In present study, the flapping mechanism developed for mimicking the flapping motion is "Crank & Rocker Mechanism". 3D models are developed of individual parts and assembled later on. Further, CAD files are converted into 2D drawings compatible with Solid Edge 21. The 2D drawings of various parts of flapping mechanism along with relevant measurements and complete assembly are shown in subsequent figures shown below.

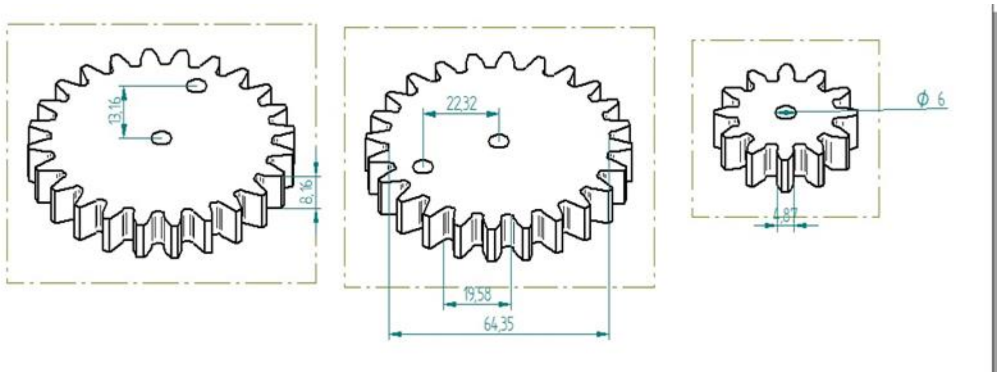

Fig. 7. Driving & Driven Gear System

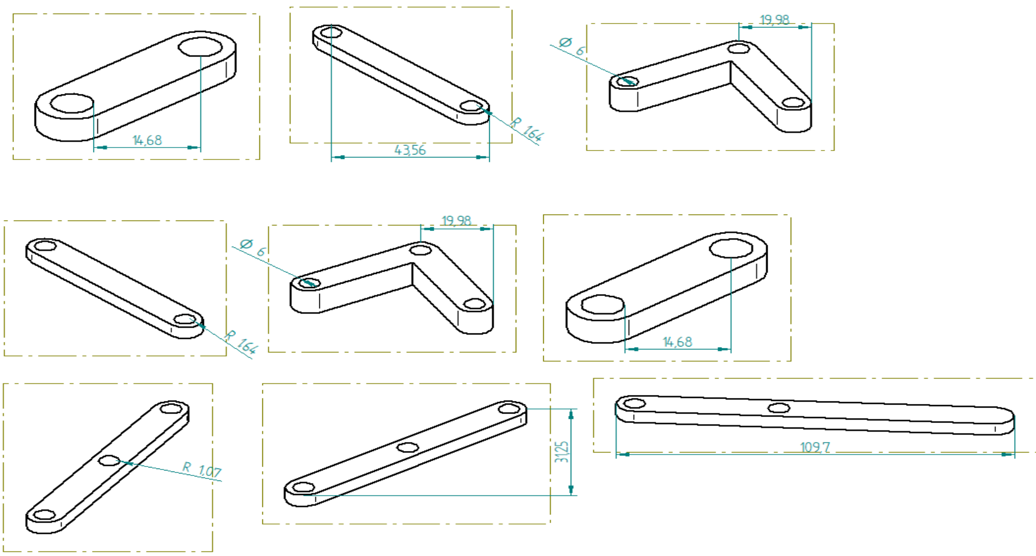

Fig. 8. Linkages Used in Transmission System (Both Left & Right Side)

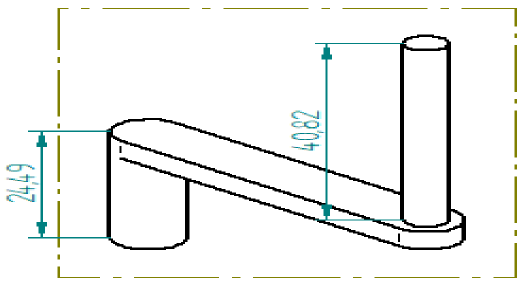

Fig. 9. Crank for Converting Rotational to Linear Translational Motion

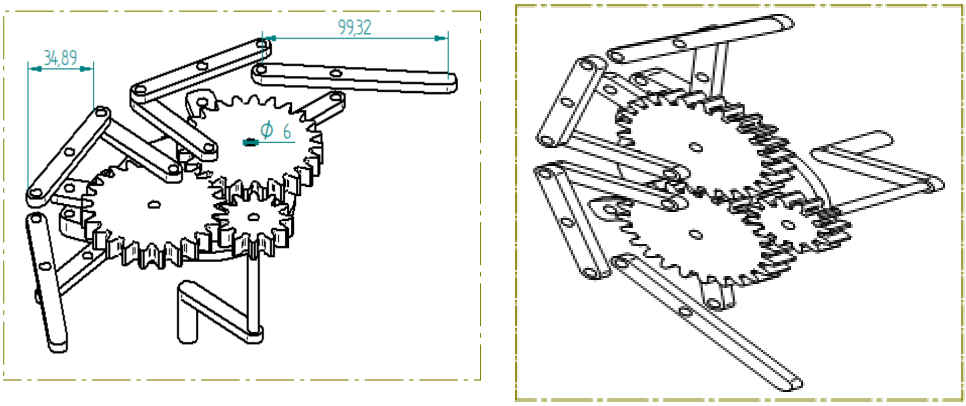

Fig. 10. Two Different Views of Complete Assembly of Flapping Mechanism (Exclusive of Flapping Wings)

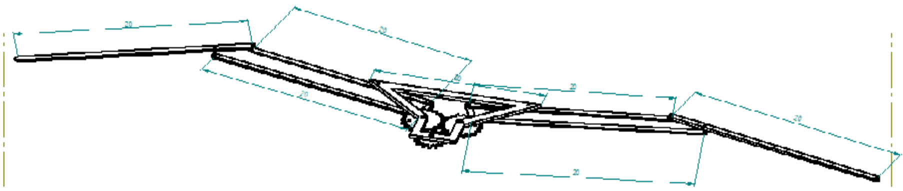

Fig. 11. Final Complete Assembly of Flapping Mechanism (Inclusive of Flapping Wings and Frame connecting Wings and Flapping Mechanism)

Conclusions

MAVs have garnered attention of researchers around the globe post World War I. Substantial number of efforts have been focused to develop the technologies regarding miniaturization. Based on type of application and demography, MAVs have been categorized into three categories. In particular, to develop a FMAV, researchers always find a source of bio-inspiration and conducts copious study to understand natural behavior of avian and insects which further enables them to understand the aerodynamics. Out of all the categories, FMAVs have attained immense popularity even after posing significant challenges to the design, thermal and material engineers. Several avian and insects have served bio-inspiration such as Hawkeye, humming bird, bumble bee, dove, dragonfly etc. In the present study, a bio-inspiration of honey bee is taken by considering the voidness in the research area pertaining to it. For replicating the flapping movement, a crank and rocker mechanism is developed based on the morphometric measurements of Apis Mellifera. The measurements of linkages have been taken approximately in the ratio of 1:10 of actual anatomical measurements. A suitable CAD software is then selected for designing and simulations. From the literature review, it is evident that SolidWorks provides user friendly and powerful engineered interface which provide freedom to a user to generate and modify the specifications. Various parts such as linkages, frames, driving system gears, flapping linkages, brackets have been designed and then assembled for a final 3D view. The 3D model is then made to undergo simulations to verify the mimicking motion. A flapping motion biomimicking honeybee is successfully designed and developed. Later on, 3D drawings are converted into another file compatible with another CAD software called Solid Edge.

Scope for future work

1. Finite Element Analysis (FEA) and Computational Fluid Dynamic (CFD) analysis can be carried out on the developed flapping mechanism. A suitable commercially available software can be selected depending on factors such as cost, complexity of structure and degree of analysis required.
2. The entire flapping mechanism 3D structure can be suitably meshed by FEM method according to time and efforts required for structural analysis such as stress, strain reactions, bending moment etc. Further CFD analysis will demonstrate the structure interaction with surrounding fluid and environmental conditions such as strong gust of wind, humidity etc.
3. A 3D model of entire mechanism along can be fabricated by using rapid prototyping methodology. For fabrication, suitable structural materials can be selected. Two such materials may be considered namely balsawood and acrylonitrile butadiene styrene (ABS).
4. A pair of flapping wing contour can be designed and fabricated resembling with Apis Melifera. The wings, then, can be suitably integrated with mechanism. Suitable material such as carbon fiber may be considered.
5. The 3D printed flapping mechanism as well as wings may be tested for stress and strains to determine statistic loading characteristics.
6. A suitable combination of power electronic gadgets can be integrated with driving mechanism and also must be capable enough to generate sufficient lift and thrust under the low Reynold’s number condition.
7. The MAV may be lifted off the ground at a height and the flight duration may be calculated for different heights.

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