

Microrobotics

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Bio Inspired Micro Robots (Propulsion and Locomotion) - Module 04

So, we have been discussing biomimicking-based structures and biomimicking-based micro robots. We have been discussing biological-based systems, like how these biological-based systems are mimicked with reference to a biomimic perspective. And we have also discussed some of the relevant applications and how they have evolved. We have been discussing the bacterial base, and with reference to the bacterial base, we were focusing more on the micro propulsion perspective. With reference to micropropulsion, we have categorized the different micropropulsion mechanisms that are evolving and how these micro propulsion mechanisms are effectively used for different functional applications. In fact, in the last model, we discussed more about these micro drones.

We were focusing on the different micro actuators that are deployed with the micro sensing elements and how these micro actuators and micro sensors are capturing different applications as well as their suitability. Now, in today's lecture, we will discuss micro mechanical flying insects because, with reference to the micro drone perspective, we are going to use a micro motor or a certain amount of micro actuation mechanisms. But when we see a honeybee or a small fly that moves, it would be better if we could look into the mechanism of how these flight motions are generated, what mechanisms are deployed, and how these mechanisms can be replicated appropriately for different applications. In this model, I will be discussing one of the key case studies of a micro mechanical flying insect.

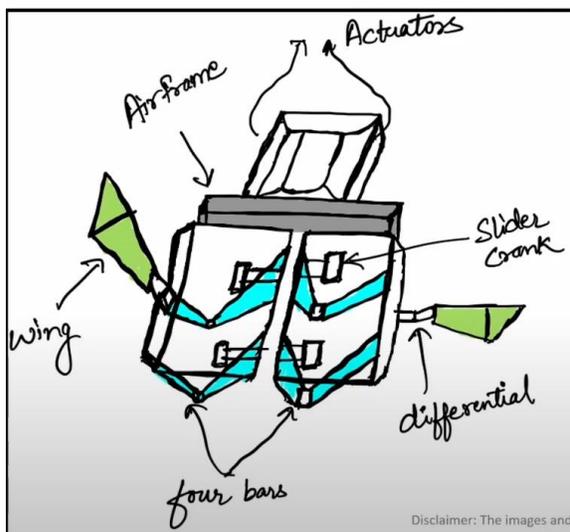
As far as these micro mechanical flying insects are concerned, these micro mechanical flying insects are miniature UAVs, which are composed of a metal body with two wings and a control system. The micro mechanical flying insect aims to create an autonomous flying robot insect that is almost the size of a house fly. To do this, biologists have identified the mechanism in the real insect that is necessary for flight, thus solving the mystery of how insects produce an adequate lift-off for stable flight. The result shows that

to produce enough lift while also having a structure that can create a thrust vector necessary for the control of the insect, there are several key kinematic and dynamic requirements. So, when we talk about MFI, the MFI wing must be capable of independently going through a wing stroke of around 120 degrees while being able to rotate at 90 degrees at a resonant frequency.

When we try to list the process parameters that have evolved, one is with reference to the wing stroke of 120 degrees and a resonant frequency of 150 hertz. To do this, the body of this micromechanical flying insect consists of two wings, each driven by a separate thoracic structure. If we look into this mechanism of this particular structure, there is an airframe and there are two actuators placed. There is a slider-crank mechanism that has a small micro four-bar chain mechanism. We have a wing structure, and there is a differential structure.

The main function of the differential structure is for the moment in a forward and return stroke, and the wing takes care of the flapping mechanism. Here, the resonant frequency is expected to be close to around 150 hertz, and the wing shape has a degree of close to around 120 degrees, and it can rotate at 90 degrees. To do this, the body of this MFI consists of two wings, as shown over here, each driven by a separate thorax structure. The thorax structure consists of two actuators. One is a mechanical actuator, like an amplifying four-bar structure, and the other one is a differential structure.

❖ Micromechanical Flying Insect(MFI)



➤ The second key design consideration is a thorax structure which can transform small piezo actuator deflections into the large wing stroke and rotation required to achieve efficient flight – a flexural 4 bar element is used to provide sufficient wing stroke, combined with a miniature differential element to provide wing rotation and A low-inertia rigid wing is fabricated from polyimide .

➤ The MFI needs to have comparable wing inertia and damping to keep Quality factor(Q) low and controllability high.

Figure: Schematic of 2 wing MFI comprising of 26 joints 4 actuators and 4 degree of freedom

→ Compare wing with. Compare air for.
Unmanned bo

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As far as the main focus of this structure is concerned, it is the air that is proportional to

the square of the wing's velocity. So, the most important requirements are the high resonant frequency and the large stroke angle. One technique for the construction of these micro robots uses micro machine silicon for linkages and hinges. Considering the material is silicon, it is lightweight and can be effectively used for joints. With reference to inertial perspective, we may discuss how these resonant frequencies can be effectively used for this inertial mechanism. This also gives rise to a higher mechanical Q, causing a decrease in controllability. Here in this case, we will be discussing the degrees of freedom involved in the overall one axis of this thorax structure. As far as material perspective is concerned, we have a carbon fiber-based structure in place. A composite wing with a composite airframe keeps the weight low, and these MFIs use a structure called unimorph base structure. These unimorph base structures are a kind of piezoelectric integrated structure.

Such actuators basically produce large forces, and they provide a small displacement that necessitates the use of a kind of mechanical amplifier for the stroke. There is an option that these actuators will either have a stainless-steel base structure, or, in certain cases, they can also have a silicon base structure. By utilizing a high stiffness-to-weight ratio of composites, these inertias can be decreased by allowing for the tailoring of this anisotropy layer. The anisotropy makes it possible to create an actuator with a kinematic property that allows for the simplification of the kinematics of the 4-bar structure. Now, when we investigate the key challenges involved here, it is microfabrication.

When we observe the microfabrication perspective, the first important construction is fiber-reinforced material for the construction of micro-devices. This links with the 4-bar structure having a size ranging from 0.5 mm to 6 mm in length and a width of 0.5 mm to 1 mm. For such kinds of honeycomb structures, using a cell wall size of the order of magnitude less than the smallest dimension of the thorax gives as low as 50 micrometers of smallest reciprocation that is being deployed.

Now when we investigate the required beam width for these fiber-reinforced composites with a fiber diameter approximated as 10 micrometers, it limits the size of the material. Using the composite of these applications, it assumes it can machine the laminates on a single ply basis down to accuracy and approximate the fiber diameter. The traditional method of cutting and handling these materials is not possible at this scale. Instead, a laser micro machine stage is used to cut the plies both in a cured and an uncured state. All the plies are designed using a two-dimensional CAD package and are laser cut automatically.

The material with a high stiffness-to-weight ratio was desired, with carbon fiber-reinforced epoxy, and experimentally, up-and-down-cued plies can be cut simultaneously. To eliminate the errors during the construction of the cut laminate, all angles are controlled with a 2D CAD layout, and the plies are aligned visually under a microscope before cutting. One of the major concerns of laser micro machining these laminates is whether to cut the composite cured or uncured. Constructing the thorax using uncured layers has the greater

benefit of being able to lay up the lamplight for the link and a polymer for the joint at one time. The cure laminate can also be deployed without the need for extra adhesive layers.

This simplifies the construction and cuts down the inertia by eliminating the need for an additional epoxy. When we investigate the micromachining behavior, these are laser-micromachined structures with a face sheet, a honeycomb section, and a molded honeycomb layer. These laser micro-machining and uncured lamina have difficulty since the laser creates localized heating, causing the epoxy matrix to flow around the cutting area and causing the laser to go out of focus. Thus, laser cutting uncured lamina is possible, but it becomes increasingly more difficult with smaller part sizes, and it is only possible for one layer at a time. Since the uncured matrix is still in a viscous state, smaller features can be easily destroyed during handling after cutting through careful practice and paying attention to these problems.

So these MFI thoraxes have evolved to be used in construction; basically, it depends on the mostly uncured layer. Now let us see the overall construction or the kind of composite laminate that is being established over here. In the structure, we have the actuator in place, and then there is a 4-bar mechanism. There are multiple composite links with the flexures incorporated. These flexures, along with the composite link, will cater to the overall flow of structures.

Now let us discuss the overall parameters that are involved in such a composite link. For maximum weight savings, the beam should not be a solid structure because, as far as this case is concerned, the overall structure is going to play a vital role with respect to deflection. When we derive the relation for a composite link, for maximum weight savings, the beam should not be a solid structure. Instead, a honeycomb configuration can be used, and the analysis done for the beam is aimed at matching the stiffness of the stainless-steel beam while minimizing the weight of the beam. So first, the stiffness of the double-supported cantilever is given by

$$k = \frac{48EI}{L^3}$$

So, the current beam has a triangular cross-section with the moment of inertia represented in the image. So, the cross-section moment of inertia of the honeycomb structure is

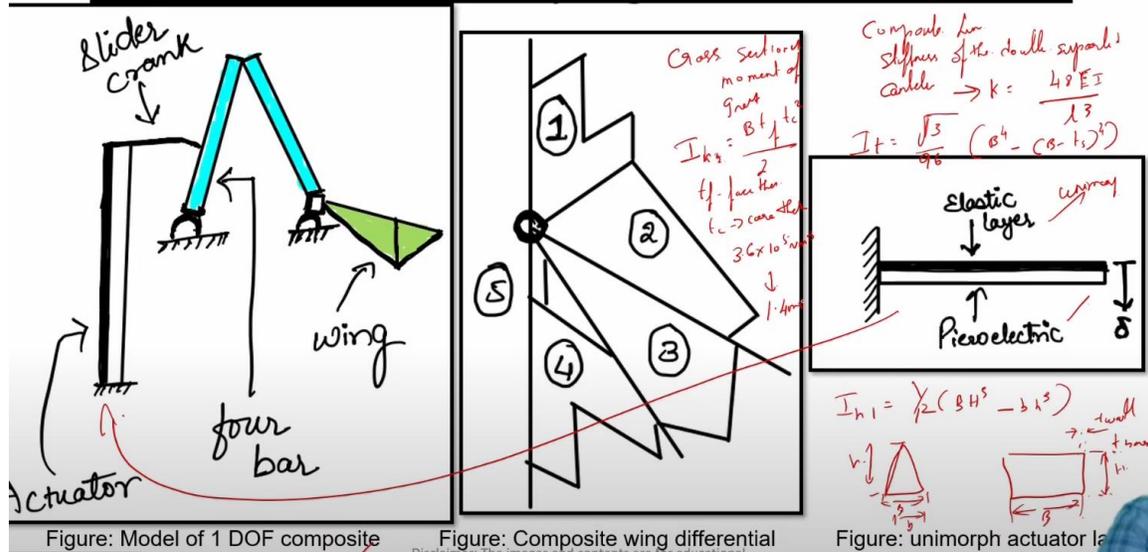
$$I_h = (1/12) (B H^3 - b h^3)$$

and

$$I_t = \frac{\sqrt{3}}{96} (B^4 - (B - t_s)4)$$

Considering the triangular cross section, it can be named as the larger b, smaller b, and this is the h corresponding to the thickness of a wall, and we have the thickness of the wall (T) and T base. From an application point of view, we have an elastic layer and the piezoelectric structure acting as an actuator. It is also referred to as an unimorph structure, where one way of actuation is taken care of by the piezoelectric structure and the return stroke is taken care of by the elastic layer.

❖ Micromechanical Flying Insect(MFI) Parts



Appropriately, the actuations are controlled and translated into the slider-crank mechanism with the four-bar and the wing arrangement. So, it is a model that caters to 1 degree of freedom as experimented. Now, when we investigate the cross-sectional moment of inertia, using the formula as mentioned in the image where t_f is the face thickness, t_c is the core thickness, and the stiffness of the beam can be represented as $3.6 \times 10^5 \text{ N/m}$, the overall weight is approximately 1.4 mg.

Now one of the major challenges involved is with reference to the joint fabrication. The four-bar is constructed by sandwiching the polyester flexure layer with the honeycomb structure, and hence there is no need for a clamp. To prevent peeling, as in this case of a steel beam structure, the final element of these 1 DOF thoraxes is the connection between the actuator and the base link. Since the actuator tip and the base link slider crank are attached at the point, it forms two intersecting arcs, and there is a need to go for an additional joint between the two. This is achieved using a traditional slider-crank mechanism, which relies on the buckling strength of the flexures to determine the serial stiffness.

Because of the non-linear motion of the actuator and the four-bar base link, this design

causes a non-linear decrease in serial stiffness, effectively creating a backlash element. This eliminates a kind of no-buckling design, which is a kind of introduction. So, when you try to investigate the kind of concept that is established over here, this is a kind of slider crank that increases the serial stiffness by ensuring that regardless of the portion of the element of the thorax, there will be a fluctuation within the slider crank that is in tension. This concept has been attempted by using standard steel beam construction. However, it is ineffective to use a construction that is bulky or required, where there is a kind of overly complex structure that fails to achieve the necessary stiffness.

So, the stiffness of the slider crank must be higher than that of the rest of the thorax links since the slider crank will experience the highest force. Also, the complexity of the structures causes alignment errors to arise, leading to kinematic singularities and an increase in the effective parallel stiffness. Thus, if the stiffness of the sections could remain high while using a planar structure to decrease complexity, the no-buckling slider crank could be made small and in an efficient form factor. Ideally, these are the concepts with reference to a no-buckling perspective. Now, if you observe, you will see a model of the completed one degree of freedom.

The results of the carbon fiber MFI thorax are compared to the results of the steel version, which is affected by the lower inertia, and the reference frequency is one of the key aspects. Now, when we investigate the overall description with reference to design and structural perspective, the biomimetic approach these MFIs mimic is the flapping wing and the kinematics of an insect called Diptera, which is a fly known for its highly maneuverable flight. It uses two intimately actuated wings like a real insect, enabling a complex flight pattern such as hovering, quick return, and stabilization. When we look into the material and fabrication perspective, it is built using a microelectromechanical system technique. In fact, we had discussed the evolution of laser fabrication that takes care of precision at a small scale.

So, the primary material basically includes a carbon fiber composite for structural strength with minimal weight. A polymer-based flexible hinge to replicate insect wing joints and a thin film piezoelectric actuator to generate the motion of a wing flapping. When we closely observe the wing mechanism and actuation, unlike traditional rotary propellers, these MFI flaps its wings using a mechanical transmission system. The overall mechanism of this mechanical transmission system is a kind of 4-bar chain mechanism designed for a flapping arrangement. The flapping motion is driven by a piezoelectric actuator, which converts electrical energy into mechanical motion through the deformation of a piezoelectric material.

When we investigate the flight mechanics and aerodynamics perspective and the flapping wing kinematics, the insect uses a unique mechanism where the wing moves in an elliptical or a numeral 8 pattern to generate lift and thrust. These MFIs replicate this kinematics to

maximize their lift production, basically at lower Reynolds numbers, so that they cater to insect-scale aerodynamics. It also reduces power consumption by utilizing passive wing deformations. When we look into the overall lift and thrust generation at small scales, traditional aerodynamics, like fixed wings, show that the propelled base systems are inefficient, and MFI then relies on unsteady aerodynamics such as delayed stall structures, where the wing remains at a high angle of attack without stalling, resulting in increased lift, rotational lift, and enhanced lift due to wing rotation at stroke reversal. A wake capture is also used where the energy from a previous stroke is recaptured for efficiency.

With reference to stability perspective, the MFI is an independent wing control like a hummingbird or insect. It performs a quick turn by altering the wing in relation to stroke and amplitude phase, and it maintains stability in turbulent environments. With reference to actuation and power system perspectives, these actuators use a piezoelectric actuator instead of a traditional motor due to size and weight constraints. These piezoelectric materials expand and contract rapidly when voltage is applied, generating wing motion in the system. When we look into the power supply perspective, these current prototypes rely on an external power source, but future iterations aim to onboard power solutions including high energy density micro batteries, energy harvesting from ambient sources, and energy sources that include solar and RF energy.

When we look into the control system perspective, to achieve autonomous flight, the MFI must integrate a lightweight high-speed sensor such as optical flow sensors for motion detection and navigation, gyroscopes and accelerometers for stability and orientation, and bio-inspired antennas or tactile sensors for environmental awareness. When we investigate the feedback control perspective, flight at such a small scale requires high-speed feedback loops to adjust the wing kinematics in real time. It has control strategies that include a proportional integral derivative controller for maintaining stable flight and a neural network-based adaptive control for mimicking insect reflexes. Some of the key features of these MFIs are that they have a flapping wing mechanism. So, ideally, it uses a piezoelectric actuator owing to the requirement of high-frequency actuation or other micro-actuators to drive the wing motion, mimic insect wing kinematics to generate lift and maneuverability.

Miniaturization and MEMS fabrication, as discussed in the past as well, are constructed using a MEMS-based lithography technique. So, the components are designed at a millimeter scale, typically a few centimeters in size, having a high wing beat frequency. It operates with a wing beat frequency like that of a real insect, close to 100 or around 100 to 200 hertz, and it also achieves rapid thrust and agility. It is a lightweight structure, typically made of a lightweight material like carbon fiber and a polymer composite. It also allows for an efficient power-to-weight ratio.

It has its own autonomous control challenges that require high-speed feedback control for stability, such as when there is a frequency with reference to a lift and a drop. So this feedback should be appropriately fed in such a way that the response time is quite low and then immediate actions can be taken. However, the current research is more focused on integrating an onboard sensor, and it is widely used for energy sources as well as energy management-related applications. Some of the key challenges that have evolved with respect to this MFI perspective are miniaturized power supply, developing an onboard power source, which remains a major challenge, and the second challenge is autonomous control. A real-time flight stabilization and navigation require an advanced microprocessor and an AI-based control for such autonomous control.

From a manufacturing precision perspective, these MEMS fabrications need to ensure high precision even at the sub-millimeter scale, and from an environmental factors point of view, these insect scale aerodynamics are highly sensitive to wind and turbulence. When we look into the future directions, there is a huge scope for wireless power solutions, inductive charging, or ambient energy harvesting systems. It is also used for advanced AI for autonomous navigation, machine learning for real-time decision making, swarm robots, a kind of coordinated movement of multiple MFIs for complex tasks, and improved materials like the development of lighter, more durable materials for longer flight endurance. So, these are some of the key challenges that will be focused on. So, in the next class, we will be discussing the algae-based micro-robots, and we will also discuss the overall mechanism involved in water striders in detail.