

Microrobotics

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Microsystem for Microrobotics (Integrated approach) - Module 05

We have been discussing the different types of MAVs, including fixed-wing type, rotary-wing type, and flapping-wing type, in detail. Whenever we are considering and designing such systems, there is a need to investigate or design the kinematics and dynamics of the systems. When we talk about kinematics and dynamics, people who have studied robotics will understand that kinematics and dynamics change with reference to the type of linkage. Here, in this particular case, we are talking about a kind of MAV. Appropriately, we may need to deploy a kind of dynamic equations, or we may need to deploy a concern parameter catering to these dynamic equations. Considering the dynamic equations, let us consider this as a plane, and the movement of the fly is from the center of mass, which is along the plane. Ideally, in this case, we consider a kind of initial frame, the final frame, and a kind of vehicle frame that is exhibited here. There are two points located in rigid body dynamics: one is OI, and the other is CM. So, this SOI CM with reference to R cube is the vector that joins the extreme border OI with the rigid body center of mass. So, V and ω are the translational and angular velocities, respectively, at any point r cubed; F and τ are the forces at any point r cubed.

Kinematics Frames

Dynamics Equations of Motion

MAV System Description

- Consider O_l and CM are two points located on the rigid body.
- $S_{ol,cm} \in R^3$ is the vector that joins extreme border O_l with rigid body's center of mass.
- V and ω are translational and angular velocities respectively at any point in the R^3 .
- f and τ are forces at any point in the R^3 .
- The kinematic transformation equation for Dragan Flyer body is given as,

$$\dot{V} = \begin{bmatrix} \dot{\omega}_{cm} \\ \dot{v}_{cm} \end{bmatrix} = I_{cm,T}^{-1} [F_{cm,T} - I_{cm,T} V_{cm}]$$

$$\dot{V} = \begin{bmatrix} J_{cm,T} - S_{ol,cm} m_T S_{ol,cm} & m_T S_{ol,cm} \\ -m_T S_{ol,cm} & m_T U \end{bmatrix}^{-1} \begin{bmatrix} \tau_{cm,T} - \tilde{\omega}_{cm} J_{cm,T} \tilde{\omega}_{cm} \\ f_{cm,T} \end{bmatrix}$$

$J_{cm,T}$ is the total inertia of the vehicle due to rotors and electronics with total mass m_T .

U is the identity operator.

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When we try to look into the kinematic transformation equation from a drag and flow body, it is given by this particular format and derivation, where this \dot{V} corresponds to the kinematic transformation of these kinds of equations. So in this particular case, when we try to look into the key parameters, the key parameters include J , which is the total inertia of the vehicle due to the rotor and the electronics, with the total mass M_T , and U is considered to be the identity operator, which persists. When we look into the dynamic equation of motion, the total inertia is represented by $J_{cm,T}$, which is calculated according to this particular equation where it depends upon the rectangular mass m_2 , m , and R_m , which contribute towards the radius of the secondary element. And when there is a spherical-shaped dragon flyer, M_1 and R are the mass and the radius, respectively, for the main electronics. A and B are the lengths of the rectangular shape for the secondary electronics that are exhibited here.

When we look at the flapping wing arrangement, these flapping wing micro aerial vehicles are a class of unmanned aerial vehicles that mimic the flight characteristics of a bird, a bat, and an insect. So, they offer a kind of unique advantage over traditional fixed-wing and rotary-wing MAVs, which includes enhanced maneuverability and also has a kind of concealment and effectiveness in lower Reynolds number environments. When we look at the performance perspective, the thrust is primarily generated by wing deformation during flapping. While lift is similar to that of a fixed-wing aircraft, with additional contributions from unsteady aerodynamic effects, the optimal flapping frequency significantly impacts performance. Whereas when we try to talk about high frequencies, these high frequencies may decrease thrust. Finding an optimal balance is crucial. In this particular case, we have

two different strokes. One is called an upstroke and the other is called a downstroke. In downstroke, we have a pronation in place, and when we try to consider an upstroke, we have a supination in place. In the case of a supination, we have orientation or a vector matter space that exhibits, and in the case of downstroke, we have pronation, which exhibits.

Dynamics Equations of Motion

Total inertia $J_{cm,T}$ is calculated according to the following equation,

$$J_{cm,T} = \frac{2}{5} M_1 r^2 + M_2 \left(\frac{a^2 + b^2}{12} + S_{mf2,cm}^2 \right) + m(r_m^2 + S_{oi,cm}^2)$$

For spherical shape DraganFlyer, M_1 and r are mass and radius respectively of main electronics.

M_2 is rectangular mass, m and r_m are mass and radius of secondary electronics and 4 rotors.

a and b are lengths of rectangular shape for the secondary electronics.

Now, when we consider flapping wing MAVs, these flapping wing MAVs are governed by a certain amount of physical principles. Some of the physical principles include Newton's law of linear motion, and they also depend upon the rate of change of linear momentum. So, basically, when we try to consider the rate of change of linear momentum, we may need to equate it with reference to applied forces. In case of an applied force, we have the gravitational force and aerodynamic force that are participating. As far as this applied force is concerned, it is governed by an equation. The overall coordination for a gravitational force, represented as G , is the acceleration due to gravity, and Fds is a kind of elemental surface force that exists. Similarly, when we try to talk about Euler's law of angular motion, in the case of Euler's law, R dash is the position vector of a small element of mass with volume v , and ρ is a type of density that exists, while g is a type of acceleration due to gravity that is present here. Now, when we try to look into the kind of flapping wing MAs, we have a wing and a body velocity. Considering only one side, the velocity of the right wing root in a body frame with reference to the inertial frame V_r wing is given by V_r wing as \bar{u} plus $\bar{\omega} \times \bar{r}$. So \bar{r} is the portion of the wing root from the main body center, U is the linear velocity, FWMAV is a type of flapping wing MAV, and α is the angular velocity here.

Flapping-Wing MAVs

Governing Physical Principles

- Newton's Law of Linear Motion: ✓

Rate of change of linear momentum = Applied force (Gravitational + Aerodynamic)

$$\frac{d}{dt} \left[\int_V \rho A \frac{d\dot{r}}{dt} dV \right] = \int_V g \rho_A dV + \int_S F ds \quad \leftarrow$$

- Euler's Law of angular motion

$$\frac{d}{dt} \left[\int_V \dot{r} \times \rho A \frac{d\dot{r}}{dt} dV \right] = \int_V \dot{r} \times g \rho_A dV + \int_S \dot{r} \times F dS$$

Where,

\dot{r} is the position vector of the small elemental mass of volume V and density ρ_A .

g is acceleration due to gravity. ✓

$F dS$ is the elemental surface forces (aerodynamics) and t is time.

So, here in this case, we have two sets. One is with reference to linear velocities, and the other one is with reference to angular velocities. With reference to the linear velocity perspective, u , v , and w are the components of the linear velocities that are focused towards the x , y , and z directions, respectively. And in the case of a particular process, we have PQR or components of angular velocities, which are represented in the x , y , z directions respectively. When we investigate the flapping wing MAVs, the wing and body velocities, the motion of the wing is with reference to the MAV. Thus, the velocities are represented as VSR wing, which are calculated with reference to the stroke, plane frame as BSR wing, which is TSRB plus U plus alpha RR. The angular velocity of the AR wing is given by AR wing as TBSR alpha plus W wing. The R wing is the portion vector of the wing element from the wing root. Rr is the position of the wing root from the main body center, u is the type of linear velocity with reference to flapping wing MAVs, and alpha is the type of angular velocity of the flapping wing MAVs. So, when we try to investigate this TBSR, it is a kind of rotational matrix which exhibits, and omega is a kind of R wing which exhibits over here.

So, when we try to observe a kind of flapping wing MAs and the wing and body velocities are concerned, we have two sets of characteristics. One is called TBR, another is T theta R, and the third is called T tr. So TBSR is TBR, T theta R, and TRR, where beta R is the deviation angle and theta R is the pitching angle, and these flapping angles are Ttr. Now, when we closely observe this deviation angle, these deviation angles are calculated with respect to the y_r stroke and the y_l stroke, and then there is a z stroke. So this z -stroke moves up and down, and appropriately we see a deviation angle, which is nothing but beta r. Similarly, when we consider an insert kind of arrangement, we have a V, an X body, an XR stroke, a Z body, and a Z stroke. In a particular case, as far as pitching angles are

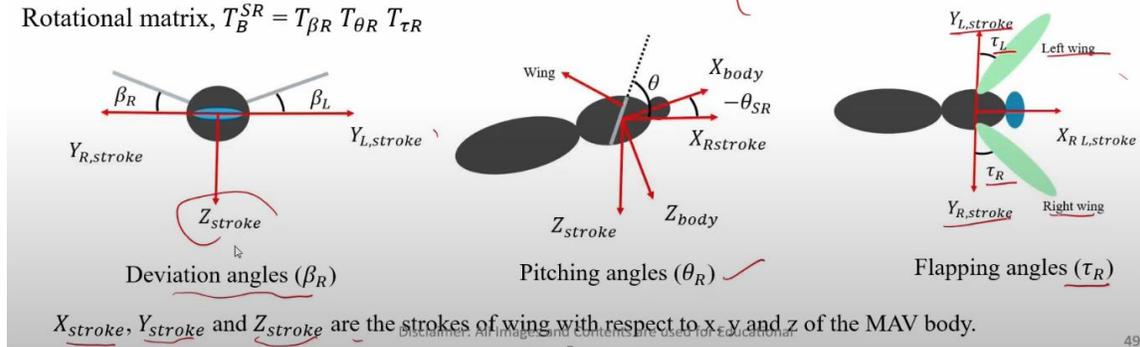
concerned. This is going to be a theta R, and this theta R and theta SR can be considered. With reference to theta and theta SR, we can find the deviation, and when we have a flapping angle, there is going to be a Tr. We have a Tr on the left and a Tr on the right.

Flapping-Wing MAVs

Wing and Body velocities:

$$T_{\beta R} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \beta_R & -\sin \beta_R \\ 0 & \sin \beta_R & \cos \beta_R \end{bmatrix}; T_{\theta R} = \begin{bmatrix} \cos \theta_R & 0 & -\sin \theta_R \\ 0 & 1 & 0 \\ \sin \theta_R & 0 & \cos \theta_R \end{bmatrix}; T_{\tau R} = \begin{bmatrix} \cos \tau_R & -\sin \tau_R & 0 \\ \sin \tau_R & \cos \tau_R & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Rotational matrix, $T_B^{SR} = T_{\beta R} T_{\theta R} T_{\tau R}$



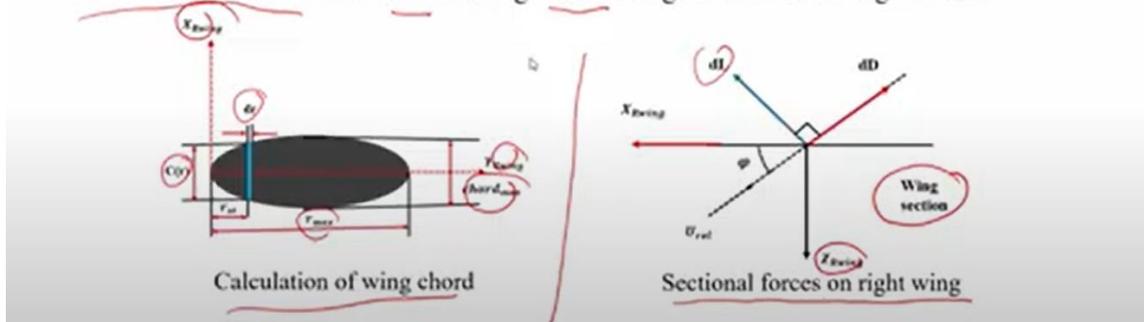
We have the YL stroke, which is exhibited, and then the YR stroke exhibits. This YL stroke will move in an appropriate direction, and the YR stroke will move in an appropriate direction. We have X stroke, Y stroke, and Z stroke, which are the strokes of the wing with respect to X, Y, and Z of the MAV. Basically, as far as these flapping wing system MAVs are concerned, there are going to be aerodynamic forces and movements. The forces and the movements are developed on the body due to the motion of the wing, so the elliptical right wing frame has the XR wing and YR wing as the X axis and Y axis, respectively.

So, let us consider R max as the total length of the wing while quad max is the maximum quad length. So, considering a small elemental step dr at a length R from the wing root, dl and dd are the differential lift and drag forces acting on the element dr. So, here DR is a chord that exists. We have an XR wing and the YR wing and chord max that exists, and then we have CR and R max that exist. Now, when we look into the sectional forces of this right wing, So, there is a wing section that exists, and there is a ZR wing, and then we have a U real, which is almost at a right angle to DL, and then there is an XR wing that pursues over here.

Flapping-Wing MAVs

Aerodynamic Forces and Moments:

- The forces and moments are developed on the body due to the motion of the wing.
 - The elliptical right wing in the right-wing frame with X_{Rwing} and Y_{Rwing} as x-axis and y-axis respectively. Let r_{max} be the total length of the wing, while $chord_{max}$ be the maximum chord length. Consider a small elemental strip dr at a length r_{st} from the wing root.
- dL and dD are the differential lift and drag forces acting on element of length dr .



Based on the frame with respect to the X_R wing and Y_R wing, the axes are appropriately assigned, and then, when we try to investigate the R_{max} perspective point of view. These R_{max} are considered to be the total length of the wing, while $chord_{max}$ is like the overall maximum chord length where a kind of strip is considered. Now, when we look into the overall aerodynamic forces and moments, the chord length of the wing is given as C_R , which is nothing but $chord_{max}$, which is a root of $1 - 4 RSC$ by $R_{max} - 1$ by 2 , the whole square root. Considering the section of the right wing in the X_R wing and Z_R wing planes. The relative velocity of air acting at the right-wing element u_{rel} is the square root of $u_{squared_r_wing}$ plus $w_{squared_r_wing}$. u_r and w_r are the velocity components in the x and z directions, respectively. The inflow angle ϕ_r is represented as $\phi_r = \tan^{-1}(w_r / u_r)$. Now the total length of this attack, which we call α_r , acting on the right wing is α_r plus θ_r by ϕ_r . So θ_r is the pitching angle and ϕ_r is the inflow angle that it exhibits. Considering the overall aspects, we are addressing the angle of attack and the pitching angle.

We are addressing the inflow, the relative velocity of air acting on the right-wing element, and the aerodynamic forces acting on the movement. When we look into this flapping wind, in terms of these aerodynamic forces and moments, we have lift (D_L) and drag (D_D) on the section. So, as far as this D_L is concerned, it is $\frac{1}{2} \rho u_{rel}^2 C_L \alpha_r C_R C_{DR}$. C_L and C_D are the coefficients of lift and drag, respectively, and ρ is the density. When we investigate the u_{rel} , the u_{rel} is the relative velocity of air acting on the right-wing element, α_r is the total angle of attack, and C_r is the width of the differential element of the wing. When we investigate the D_D perspective, it is a section that exhibits $\frac{1}{2} \rho U_{rel}^2 C_d \alpha_r C_r dr$, which is exhibited over here. So, we have been discussing these different forces that are involved in it and the moments that are being developed in it with reference to the overall flapping wing force and the overall right wing forces, etc. So, we have discussed the aerodynamic forces and their movements. And then

we have also discussed the lift and drag overall calculations with reference to the force acting on the wing element, with the DFR wing and the moment acting on the wing element. D_l and D_r are the different lift and drag forces acting on the differential element of the right wing, and ϕ_r is the inflow angle, and r_{wing} is the position vector of the wing element.

These differential forces and moments are integrated along the left side. So, we have gained clarity about the different types of micro aerial robots, as well as the micro assembly of micro aerial robots, and what the different factors being deployed are that take care of the overall requirements or overall design of the system. Now we will discuss the multi-robot system. As far as these multi-robot systems are concerned, ideally in this multi-robot system we have multiple robots that try to interact with each other, and they collaboratively perform tasks. In fact, now there is also a buzzword on cobotics; almost it is a kind of similar system that exhibits on a micro level. As far as these multi-robot systems are concerned, these multi-robot systems refer to a group of robots working collaboratively to perform tasks at micro and nano scales. So, these systems are distinguished by their capacity to communicate information. It is also meant for coordinating the activities, and it is also useful for collaborative functions, and it also takes care of executing a difficult task. So, these systems are particularly useful for biomedical applications especially for microassembly, swarm intelligence studies and the targeted drug delivery. Ideally, wherever we need to have a particular portion, we can just reach a specific task, and we can disperse the delivery.

In the case of this multi-robot system, when examining its multi-robot functionality, it should be a robust system with high enough capabilities. Although it operates on a micron level, it is subjected to a wide variety of loads that act upon it. So appropriately, the system should be robust, and there should be a kind of distributed action that exists within the system so that these distributed actions are capable enough to have the flexibility to interact and appropriately create motion. Third is with reference to the fast execution of tasks; it should have the capability to achieve a high processing speed so that it can interact in a more advanced manner. Additionally, it should have a broad range of capabilities to cater to different tasks, including the flow of the system, interaction with the system, communication among components, and ultimately creating an environment over a larger area. With reference to this system, it offers a broader coverage; as far as this broader coverage is concerned, it involves more interaction within a wider network, appropriately coordinating with that network. So, as far as these multi-robot systems are concerned, we have two different systems that exist as principles when we try to look into the principles of multi-robot systems. So, we have swarm intelligence. So, this swarm intelligence basically refers to the ability of multiple simple agents to work together in a coordinated way. It is inspired by biological systems like ant colonies, fish schools, and bird flocks, and the key swarm behavior includes self-organization.

These micro robots dynamically organize without any central control. The second most important aspect is with reference to this emergent behavior. It has a collective intelligence that arises from local interaction. As far as local interaction is concerned, it tries to behave in an appropriate way. From a scalability perspective, the system functions well regardless of the number of micro-robots.

It can maintain a particular scale and be oriented. When we look into the communication mechanisms, micro robots in an MRS can communicate in a better way, and they have good physical interactions, such as when these robots bump into each other, forming a kind of temporary structure. From a chemical signaling perspective, similar to ant trails, these robots can modify their environment to leave information for others. In case of any ant you have also seen, you might have observed. They try to create a kind of droplet, and the next ant that comes will start following this particular ant.

So, in a similar fashion, a kind of chemical signal can also be deployed. One of the important communications is with respect to electromagnetic or optical signaling. As far as this electromagnetic or optical signaling is concerned, it is used in an external control method so that it can interact appropriately. These are some of the key functionalities or characteristics with reference to multi-robot systems concerning SWAM intelligence and communication. Now, if we closely observe this multi-robot system, we see a decentralized versus centralized control.

As far as centralized control is concerned, a central unit assigns a task to each micro robot with reference to a positive aspect point of view; it has high precision and well-coordinated movement. However, with reference to a negative perspective, it is a single point of failure risk and has a communication overhead. With reference to the decentralization perspective, each micro robot makes a local decision based on the environmental cues. As far as the pro's perspective, it has a robust adaptive and scalable approach, and with respect to the negative perspective, that is, with respect to the disadvantages, it is highly difficult to achieve such a complex task without any direct coordination. In the case of a decentralized system and a centralized system, appropriately based on the application, we can develop a system for a micro robot, and in the case of a decentralized system, we appropriately apply a kind of local addition for this particular system.

Now, if you try to look into the overall coordination of this multi-robot system, there will be a central system in place, composed of several central control units and several agents. These agents, WAM, can accept the unified scheduling of the central control unit, complete their respective subtasks, and finally cooperate to complete an agreeable main task. Each of their agent members can achieve these subtasks, such as positioning, tracking, as well as visual signaling. Now, in this particular case, this CCU is considered to be the centralized control system, and then we have a kind of multiple system that has a kind of agent

members. Through this centralized system, coordination happens appropriately among the agent members, and then there will be a kind of continuous motion that persists.

So this is a kind of centralized system; this is the overall configuration of a centralized system. Similarly, when we try to talk about a decentralized system in terms of coordinating this multi-robot system, we adopt a decentralized approach. It basically eliminates the dependency on a central controller, and it enhances the system's resilience and flexibility. As far as this computational task is concerned, this computational task is performed by one or more robots in a team. Ideally, as far as this particular computational task is concerned, one main center coordinating multiple robots will perform the task and will try to deliver the appropriate specific configurations to the multiple systems.

As far as this particular case is concerned, there are no specific leaders throughout the machine, and it allows all the other robots to proceed with their computation even if one of the robots fails; that is one advantage of this decentralized system. Now there is a different configuration that exists, which is called a distributed system. As far as this distributed system is concerned, these distributed control systems also play an essential role with reference to SWAM robots. The distributed system is a kind of multilevel computer system with a communication network as the link, and it is composed of process control and monitoring. As far as this system is concerned, we have a target, there are robots in place, and there is an average portion in place.

It is integrated with the computer and communication, and it is meant for displaying and controlling the technology. So, as far as this particular case is concerned, one of the key ideas of this decentralized control system is that it has a kind of centralized operation with a kind of hierarchical management. Since you have a kind of centralized portion, it will decide the influence of the robot or its participation in a particular operation or management. So this system has a capability towards flexible interaction, flexible transformation, or flexible configuration based on the convenient configuration. As far as this particular case is concerned, the distributed control system has a relative advantage, and it has a kind of disease factor in reference to this multi-robot system compared to the centralized system.

So, ideally this has better advantages, such as when you have multiple micro robots, whether they are in the form of a swan base, an aerial vehicle, or a caterpillar-like arrangement. This communication between the caterpillar arrangement and the aerial vehicle can happen appropriately so that it can be helpful for us to emphasize a particular configuration. This is one of the key aspects that should be considered with reference to this multi-robot system. Overall, if you try to look at the picture, we have the robotic systems in place, their average position at the target, and appropriate calculations maintained in such a way that there is a kind of optimum movement that exists. So, overall

in this module, we discussed the different micro assemblies and micro assembly performances.

We also discussed this micro aerial vehicle, including the different parameters involved with reference to the design of these micro aerial vehicles, the overall links, and the mechanisms. And then we had also discussed the different types of multi-robot systems and how these multi-robot systems are deployed for different applications. So, these are some of the references that we have used for preparing these particular aspects or topics related to microassembly for micro robots. So, the next module will be focusing on biomimicking.