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AXIOMATIC DESIGN OF A WING DRIVING MECHANISM FOR MICRO AIR VEHICLE WITH FLAPPING MOTION

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ABSTRACT

Recently Micro Air Vehicles (MAVs) imitating the mechanism of birds or insects have been developed. As hummingbirds' characteristics are regarded as an appropriate candidate for MAV model, the studies of hummingbirds' aerodynamics and mechanics in relation to MAV are conducted. In this paper, an axiomatic design approach to develop a wing driving mechanism for MAV mimicking hummingbirds is proposed. Functional requirements (FRs) for the mechanism are defined through the analysis of the hummingbirds' wing motions involving hovering, forward, and backward flight. Five FRs are introduced at the highest level. Constraints (Cs) in size and weight are taken from the limitation employed in the Defense Advanced Research Projects Agency's MAV program. Design parameters (DPs) are conceived in physical domain to satisfy these specified FRs and Cs. Through the process of mapping and zigzagging to decompose to the next level, totally fifteen FRs and the same number of DPs are defined. The wing driving mechanism design is proved to be decoupled by design equation. Also we can reduce the complexity of the mechanism by physical integration.

Keywords: MAV, wing driving mechanism, axiomatic design.

1 INTRODUCTION

By imitating nature, human beings have developed new mechanisms, design skills, and manufacturing technologies. According to this, bio-mimetic technology which artificially imitates the various useful functions of bio-systems to apply to the industries has emerged. Also the efforts are made to develop existing machines and control technology by mimicking the mechanism of well working organisms. As a part of these attempts the micro air vehicle mimicking birds or flies are being developed. The conventional aerodynamic technology is applied to a large airplane very well. However, it is difficult to apply it to micro air vehicles like as small size birds or flies. Recently, many studies concerning the mechanism of hummingbirds and flies have been carried out for the application to micro air vehicles.

In this paper, an axiomatic design approach to the conceptual design of a wing driving mechanism for micro air vehicle (MAV) is proposed. The main function of this mechanism is to have the flapping motion which mimics hummingbird wing motion. First, the characteristics of hummingbirds involving forward, backward and hovering flight are examined. Second, the functional requirements (FRs) of the mechanism to have these characteristics are defined. The constraints are taken from the limitations of MAV specified by the Defense Advanced Research Projects Agency (DARPA) MAV program. A ceramic multilayer PZT bender actuator is selected to drive wings because of its light weight, relative big force generation and easy controllability. Considering the characteristics of the actuator feature and constraints, the design parameters (DPs) to satisfy FRs are created and selected in the physical region. Through the mapping and zigzagging process, the conceptual design is decomposed to the next level, and whether the design is coupled or not is checked by the design equation. Also through the detailed design a MAV prototype model is developed, and the flapping wing motion of the prototype is tested. Moreover the weight and volume of the model can be reduced by physical integration and rearrangement of DPs.

2 HUMMINGBIRD FLIGHT CHARACTERISTICS

2.1 WING BONE STRUCTURE CHARACTERISTICS

From the Fall of 1997, Alex Meyer and Stephen Serniak, of IMB, have studied the motion of hummingbird wings in hovering flight to adapt hummingbird characteristics to micro air vehicles. According to their studies, while ordinary birds articulate their wings at the shoulder, wrist and elbow, hummingbirds cannot articulate at the elbow and wrist, but the wing is free to rotate in all directions at the shoulder joint. The hummingbird's unusual arrangement of bone composition makes it possible to generate propulsive from both the down beat and up beat of its wings [2].

2.2 FLIGHT CHARACTERISTICS

From the examination of hummingbird wing motion involving the forward, backward and hovering flight, the tip traces of wings are observed to draw various ellipsoidal patterns while forward and backward flight, or an orbit like '∞' while hovering flight. Generally, the motion of a bird is characterized by three motions, which are flapping, lagging, and feathering motion. Also during hovering flight, the direction change of the wing is occurred as it completes its cycle. It makes two 180 ° turns in order to create the orbit. The wing had a pitch angle at every up-down stroke. Also hummingbirds change the attitude of body according to flight mode in order to change the angle of stroke plane and move the center of body mass. Furthermore the propulsive force direction of each wing is controlled individually. This characteristics help to change the flight direction.

Therefore the mechanism should drive wings in all directions to follow the patterns of hummingbird wing tip trace in every flight mode. Also the wing structure of MAV should have pitch angle at each stroke. Moreover the direction of propulsive force or the center of mass can be changed.

3 FUNCTIONAL REQURIEMENTS

From the characteristics of the hummingbird flight motion, the five functional requirements (FRs) for a wing driving mechanism with flapping motion are defined at the highest level.

FR1: Enable up-down wing strokes.

This is the flapping motion of wings. The up-down stroke of wing generates the main propulsive force for forward, backward, hovering flight and changing flight direction.

FR2: Enable forward-backward wing strokes.

This lagging motion of wings enables to increase the aerodynamic efficiency of flapping motion to generate the propulsive force by controlling air flow during up-down stroke.

FR3: Linking up-down and forward-backward wing strokes.

The ellipsoidal motion of wings can be realized by relating flapping motion with lagging motion. Therefore, linking the up-down and the forward-backward strokes is needed.

FR4: Enable feathering pitch motion.

The elastic deformation of feathers caused by air resistant force makes the feathering motion of wings. Therefore the flexible wing material is needed that can drive air flow to generate propulsive force, and at the same time should be bended by air resistant force while up and down stroke.

FR5: Enable controlling the propulsive force direction of each wing.

To change flight direction, hummingbirds control the propulsive force direction of each wing individually and lean their body. Thus the mechanism can control the propulsive force direction of each wing individually.

4 CONSTRAINTS

According to the definition employed in DARPA's program, MAVs must be limited in size less than 15 centimeters, have total weights of 100 grams or less and be capable of staying aloft for 20 to 60 minutes for a distance of 10 kilometers at more than 30 kilometers per hour. MAVs must carry a power supply and equipments for its autonomous operations to complete their mission individually. Therefore the wing driving mechanism must be less than 15 centimeters including each wing, and must be limited in weight to 20 grams totally considering the weights of a power supply and other equipments for operation.

5 SELECTION OF ACTUATOR

The commercial motors or engines are not suitable for MAVs with flapping motion in size and wight to satisfy the constraints. Therefore an actuator is needed that has a small size, light weight, and generates enough force to drive wings.

Piezoelectricity is a property of certain classes of crystalline materials. When mechanical pressure is applied to one of these materials, the crystalline structure produces a voltage proportional to the pressure. Conversely, when an electric field is applied, the structure changes shape producing dimensional changes in the material [3]. PZT actuators with these characteristics have small dimensional changes, but generate a large force. PZT materials can achieve a strain on the order of 1/1000 (0.1%); this means that a 100 mm long PZT actuator can expand by 100 micrometers. PZTs can be designed to move heavy loads (several tons) or can be made to move lighter loads at frequencies of several tens of kHz [4]. Also they are several centimeters in size and controllable just with voltage. Thus they can be used for MAVs with the amplifying mechanism.

There are several types of PZT actuators, which are stack, bender, and disk type PZT actuators. Among these, even though a ceramic multilayer bender type PZT actuator has a small blocking force relatively, it generates a large displacement, and it is easy to amplify the deflection. Therefore, the bender type PZT actuators are selected.

6 DESIGN PARAMETERS AND ZIGZAGGING

In consideration of the feature and the motion of the ceramic multilayer bender PZT actuator, the design parameters (DPs) to achieve FRs are conceived in the physical region. At the highest level DPs are selected as follows.

DP1: An Up-down wing driving mechanism.
DP2: A Forward-backward wing driving mechanism.
DP3: A Linking mechanism.
DP4: A Feathering mechanism.
DP5: A propulsive force direction driving mechanism.

The design equation (1) composed of FRs and DPs at the highest level proves that the design is decoupled. Notice that the up-down wing driving mechanism and the forward-backward wing driving mechanism are related with the linking mechanism.

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{Bmatrix} = \begin{bmatrix} \times & O & \times & O & O \\ O & \times & \times & O & O \\ O & O & \times & O & O \\ O & O & O & \times & O \\ O & O & O & O & \times \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{Bmatrix} \quad (1)$$

The DPs of the highest level are decomposed to the next level through the zigzagging process, and the FRs of the next level and DPs are defined.

6.1 AN UP-DOWN WING DRIVING MECHANISM

This mechanism makes the flapping motion of wings which generates main propulsive force of vehicle during forward, backward, hovering flight and changing flight direction. The FRs of this mechanism are defined as follows.

FR11: Amplifying the deflection of PZT bender actuator for up-down strokes.

Generally, the ceramic multilayer bender actuator has a several hundred micrometers deflection. It is not enough to drive wings directly to make a stroke motion. Therefore the deflection of PZT bender actuator needs amplifying.

FR12: Changing the driving direction of PZT bender actuator for up-down strokes.

It is needed to change the direction of deflection in order to link up-down and forward-backward strokes, and to enable the rearrangement of the DPs for reducing the size of MAV.

FR13: Supporting the elements for up-down strokes.

It is necessary to support PZT actuators and other elements.

The DPs to fulfill these FRs are created or defined as follows.

DP11: A rotor.

The rotor is fixed with a shaft and has a slot to transfer the tip deflection of the PZT actuator to swing motion. The swing angle can be changed by the amount of deflection or by the distance between the actuator tip and the rotation center.

DP12: A pole.

The pole is fixed to the rotor to amplify the swing motion, and it can change the direction of swing by changing the fixing point.

DP13: A body.

The body supports PZT actuator and rotor.

The design equation (2) composed of above FRs and DPs proves that the design is decoupled. Notice that DP11 and DP12 are related to amplifying the deflection of PZT actuator.

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} \times & \times & O \\ O & \times & O \\ O & O & \times \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix} \quad (2)$$

6.2 A FORWARD-BACKWARD WING DRIVING MECHANISM

The Forward-backward wing driving mechanism has the same FRs and DPs with the up-down wing driving mechanism. The relative position between them is considered to link each other's motion. The motion of this mechanism is arranged perpendicularly to the motion of the up-down wing driving mechanism.

FR21: Amplifying the deflection of PZT actuator for forward-backward strokes.

FR22: Changing the driving direction of PZT actuator for forward-backward strokes.

FR23: Supporting the elements of mechanism for forward-backward strokes.

DP21: A rotor.
DP22: A pole.
DP23: A body.

In the same way, the design equation (3) composed of above FRs and DPs shows that the design is decoupled.

$$\begin{Bmatrix} FR21 \\ FR22 \\ FR23 \end{Bmatrix} = \begin{bmatrix} \times & \times & O \\ O & \times & O \\ O & O & \times \end{bmatrix} \begin{Bmatrix} DP21 \\ DP22 \\ DP23 \end{Bmatrix} \quad (3)$$

6.3 A LINKING MECHANISM

This mechanism links the up-down swing pole motion with the forward-backward swing pole motion. As the two degree of wing motion can be realize by this mechanism, the ellipsoidal patterns of wing tip can be traced. The FRs of this mechanism are defined as follows.

FR31: Linking Up-down wing driving pole.
FR32: Linking Forward-Backward wing driving pole.
FR33: Limiting up-down wing motion.
FR34: Limiting Forward-Backward wing motion.

It is needed to support the linking element and at the same time to limit the angle of swing motion.

To satisfy the FRs of the linking mechanism, DPs are conceived as follows.

DP31: A flapping link.
DP32: A lagging link.
DP33: A flapping guide.
DP34: A lagging guide.

The design equation (4) composed of above FRs and DPs proves that the design is decoupled. Notice that the guides are related to two links in the function of supporting the links and limiting the swing motion.

$$\begin{Bmatrix} FR31 \\ FR32 \\ FR33 \\ FR34 \end{Bmatrix} = \begin{bmatrix} \times & O & O & O \\ O & \times & O & O \\ \times & O & \times & O \\ \times & \times & O & \times \end{bmatrix} \begin{Bmatrix} DP31 \\ DP32 \\ DP33 \\ DP34 \end{Bmatrix} \quad (4)$$

6.4 A WING FEATHER DRIVING MECHANISM

The feathering motion of hummingbird is derived from the elastic deformation of feathers caused by air resistant force. A flexible wing that can drive air flow and can be bended by air resistance to generate propulsive force during up-down strokes is needed. The FRs of this mechanism are defined as follows.

FR41: Supporting feather.
FR42: Driving air flow.
FR43: Making elasticity of feather.

To satisfy the upper FRs of a feathering mechanism, DPs are conceived as follows.

DP41: A wing pole.
DP42: A wing plate.
DP43: A feather pole.

The design equation (5) composed of above FRs and DPs shows that the design is decoupled. That is why the feather pole supports wing plate too.

$$\begin{Bmatrix} FR41 \\ FR42 \\ FR43 \end{Bmatrix} = \begin{bmatrix} \times & O & \times \\ O & \times & O \\ O & O & \times \end{bmatrix} \begin{Bmatrix} DP41 \\ DP42 \\ DP43 \end{Bmatrix} \quad (5)$$

6.5 A PROPULSIVE FORCE DIRECTION DRIVING MECHANISM

To control the direction of flight, hummingbird changes the direction of each wing's propulsive force individually. Also it lean body to move the center of mass according to the flight direction. This function can be realized by rotating the left and the right side wing driving mechanism individually. The FRs and DPs of this mechanism are listed as follows.

FR51: Rotating the left wing driving mechanism.
FR52: Rotating the right wing driving mechanism.

DP51: A Left-side RC-Motor.
DP52: A Right-side RC-Motor.

The design equation (6) composed of above FRs and DPs proves that the design is uncoupled.

$$\begin{Bmatrix} FR51 \\ FR52 \end{Bmatrix} = \begin{bmatrix} \times & O \\ O & \times \end{bmatrix} \begin{Bmatrix} DP51 \\ DP52 \end{Bmatrix} \quad (6)$$

7 THE RELATION OF ALL FRs & DPs

The relation among total FRs and DPs is presented by table 1. The design is proved to be a decoupled design like as the highest level design equation. As the deflection of the PZT actuator is amplified by the up-down wing driving mechanism and the linking mechanism, total 4 DPs are related to drive one side wing. Also the change of deflection direction is related in the same way. Therefore in the detailed design, the dimensions of elements for torques and the stroke angle should be determined considering related DPs.

Table 1. Total FRs & DPs relation

		DP1			DP2			DP3				DP4			DP5	
		DP11	DP12	DP13	DP21	DP22	DP23	DP34	DP33	DP32	DP31	DP41	DP42	DP43	DP51	DP52
FR1	FR11	>	>						×		×					
	FR12		>								×					
	FR13			>												
FR2	FR21				>	>		×		×						
	FR22					>				×						
	FR23						>									
FR3	FR34							>		>	>					
	FR33								>		>					
	FR32									>						
	FR31										>					
FR4	FR41											>		>		
	FR42												>			
	FR43													>		
FR5	FR51														>	
	FR52															>

8 A DETAILED DESIGN AND A PHYSICAL INTEGRATION

The detailed design of every mechanism based on the conceptual design using the axiomatic design approach is conducted. The figure 1 shows the prototype MAV model without the propulsive force direction driving mechanism. The complexity of the mechanism is reduced by physical integration of flapping and lagging guides. In figure 2, all guides of the MAV model are physically integrated, and the guide is fixed to lagging pole. Also the up-down wing driving mechanism and the forward-backward wing driving mechanism are rearranged in parallel. The physical integration and the rearrangement make the mechanism simple in structure and reduce the weight and volume of the MAVs. The specification of the MAV models is shown in table 2 such as the stroke angle, dimension, the weight without PZT actuator, and torques.

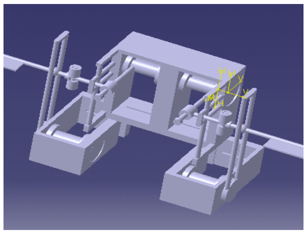

Figure 1.The Prototype MAV Model

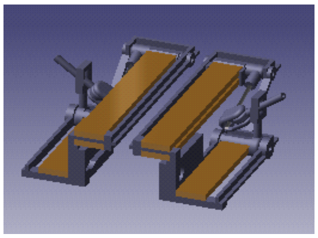

Figure 2.A MAV model after physical integration and rearrangement of DPs.

Table 2.Specification of MAV models

	Model 1	Model 2
Stroke angle	±40° ±60°	±77° ±41°
Torque	0.596 Nmm	1.99 Nmm
Dimension (mm)	55×38×58	50×58×18
Weight	10 g	5.4 g

9 CONCLUSION

The axiomatic design approach to the conceptual design of a wing driving mechanism for MAV with the flapping motion which mimicking hummingbird wing motions was proposed. The FRs of a wing driving mechanism were derived from the analysis of the characteristics of hummingbird flight. The weight and the volume of MAV can be reduced by the physical integration and the rearrangement of DPs.

Consequently, in relation to bio-mimetic technology the axiomatic design methodology is useful to analyze the FRs and DPs of a bio-system and to develop the mimicking system.

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