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The Research and Design of Experimental Prototype in Flapping-Wing Micro-Air-Vehicles

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Abstract

To get first-hand data of test in flapping wing flight, a Flapping-wing Micro-Air-Vehicles experimental prototype was designed. This test prototype was constructed by using the theory of bionics and Micro-Air-Vehicles (MAV) design. Adopts Size-law to determine the initial design parameters; modal analysis to design the structure of the flapping-wings; hirao tail capacity, static stability to design the spoiler and Four-link theory to design the transmission system. With those theory, the test prototype was realized and can flying in the air. The process of prototype design not only provides a useful reference experience for subsequent design in testing prototype, but also provide an experimental platform for the upcoming wind tunnel experiments.

Keywords: Flapping-wing aircraft; Experimental prototype; Wing; Spoiler; Transmission system

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INTRODUCTION

Recent years have seen the increasing popularity of Micro-Air-Vehicles (MAV) as their applications range from the military, surveillance, planetary exploration, search-and-rescue to many more (Michael & Fenelon, 2010). So far has no precise definition on MAV, generally, the MAV should satisfy the following requirements proposed by DARPA (Li, Song, B. & Song, 2003; Hu, Kumar, Gregg, & Roberto, 2010):

(a) Characterized by small vehicle size (<15 cm), low flight speed (<10 m/s), life time 20~60 min.
(b) Control over a radius of 10 km, and can carry the load 20g day and night.
(c) Real-time transmission of images in day and night with autonomous flight.
(d) Flight by flapping wings used man-made power.

As an emerging technology, the development of Flapping-wing Micro-Air-Vehicles (FMAV, part of MAV) requires a lot of new aircraft designs concept that different from traditional's, these new concepts related to aerodynamic, structural, control and propulsion, etc.; FMAV's design is an inter-disciplinary, multi-field crossing subject which involving aerodynamic science, structural mechanics, bionics, micro-mechanics and other different areas. As a huge project to design a practical FMAV, a lot of in-depth research is required (Tri Quang, Vu Hoang, Sanjay, Hoon, 2014; Taro, Kazuaki, Shinnosuke, 2008; Albertani, Stanford, Hubner, & Ifju, 2007).

In order to get first-hand of test data and provide a test platform in FMAV's research and design, a test prototype was designed. In this paper,we focus on the following aspects of the test prototype: initial design parameter setting, wings, spoiler, deceleration system and transmission system.

1. THE SETTING OF INITIAL DESIGN PARAMETERS

Before presenting a detailed discussion of flapping wing design, it is important to understand the nomenclature characterizing the geometric and kinematic parameters specific to flapping wing vehicles (much of this terminology is borrowed from the nomenclature of insect biology). The geometric terminologies are as follows: Leading Edge—the edge of the wing that meets the airflow first. Trailing Edge—the edge opposite to the leading edge. Wing span—the length between the tips of the wings when they are out stretched laterally. Wing length—the base-to-tip length of one wing. Wing chord—the section between the leading and trailing edge of the wing at any position along the span. Geometric Angle of Attack—*α*, the angle the wing chord makes with the free stream velocity vector. Effective Angle of Attack—*α*′, the angle the wing chord makes with the locally deflected free steam velocity vector (Sanjay, 2006). All the parameters are shown in Figure 1.

A shows a generic insect showing the geometric parameters relevant in flapping wing air vehicles. B shows the cross section of the wing and the geometric *α* and the effective angle of attack *α*′, where U is the free stream velocity and U’+U is the locally deflected stream (Hu, Kumar, Gregg, & Roberto, 2010).

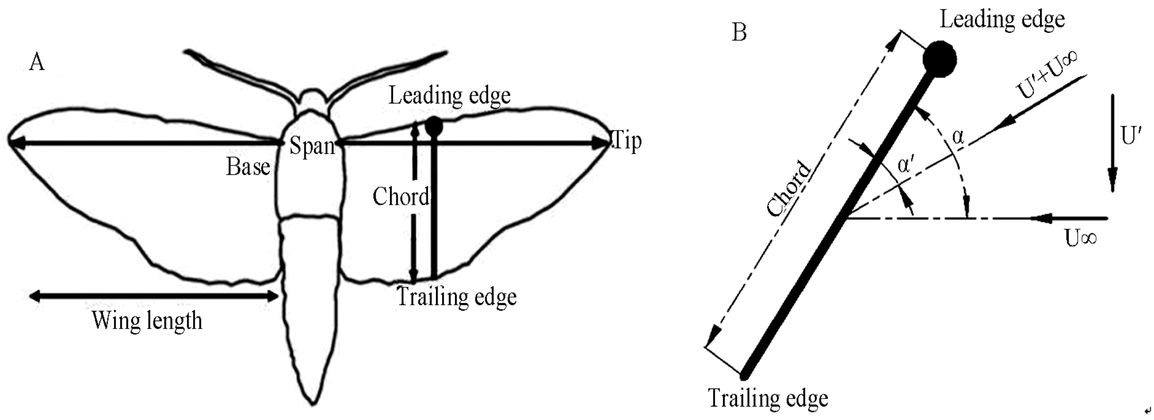

Figure 1
Geometric Parameters Relevant in Flapping Wing Air Vehicles

Under the existing design capabilities and manufacturing technologies, setting the initial weight of whole machine in 320g. In FMAV design, consider the size effect law is to evaluate various physical parameters’s (such as wing area, aspect ratio, etc.) intrinsic connection and the impact on flight characteristics, which not only helps to birds, insects and other animals flying mechanism but also helps to people find the law that could utilized by design FMAV (Wei, Mats Bergand, 1999). To a certain group or a number of different animal species, it is very easy to understand a problem when linked the uncertain parameters by dimensional analysis. By size scaling and proportion translated (dimensional analysis), one can predict the parameters (such as wingspan) versus other parameters (such as mass), which FMAV design is necessary.

The initial design parameters of FMAV are setting by the size effect law on references (Liu, Fang, Hou, & Wu, 2005).

Table 1
Power Function Relationship Between Flight Parameters and the Overall Mass
(where *M* is the total mass of the aircraft，Unit: kg)

	Dimensional analysis	Statistical formula	Aircraft parameters in this paper
Wing area /m^2	$\infty M^{0.67}$	$0.164M^{0.667}$	0.1519
Span /m	$\infty M^{0.33}$	$1.237M^{0.368}$	0.8133
Aspect ratio	$\infty M^{0.061}$	$9.339M^{0.069}$	8.6329
Flapping wing frequency /Hz	$\infty M^{-0.03}$	$3.991M^{-.064}$	8.2753
Minimum power speed/ m/s	$\infty M^{0.17}$	$8.704M^{0.158}$	7.2700

2. WING DESIGN OF FMAV

For now, the study found that the main reason impact of small aspect ratio ofwing dynamic characteristics is wing shape, aspect ratio and Reynolds. Below the paper, using wing shape and aspect ratio as design parameters in FMAV wing structure design. Here we use references’s method (Chen, Weng, & Ding, 2013), as is shown in Fig. 2, k1 ~ k17 to decide bionic flapping wing shape and position of the key points veins，*R* is the wingspan, *C* is the chord length, aspect ratio $r = R/C$. Outline shape using a sine function’s characteristics superposition with other functions (such as linear function) to the formation of the outer contour of the wing.

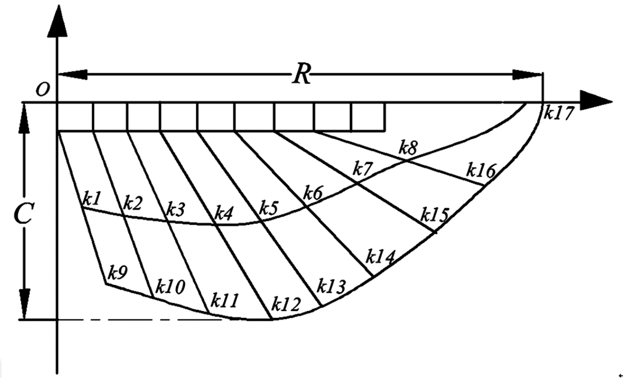

Figure 2
Design of the Wings Structural Shape

To wing structure design, from the point of view of modal analysis, when considering the lower mode dynamic characteristics of indicators only, therefore：

$$(K_A^0 + K_B^0)\Phi^0 = (M_A^0 + M_B^0)\Phi^0\Lambda^0 \quad , \tag{1}$$

$$\Phi_r^{0T}(K_A^0 + K_B^0)\Phi_r^0 = \Lambda_r^0, \Phi_r^{0T}(M_A^0 + M_B^0)\Phi_r^0 = E_r, \tag{2}$$

where: M_A^0, K_A^0 is the mass matrix and stiffness matrix of the initial structure; M_B^0, K_B^0 is the mass matrix and stiffness matrix of the designed structure. Λ^0, Φ^0 is the natural frequencies and mode shapes of the design structure matrix; $\Phi_r^0 = [\phi_1^0 \quad \phi_2^0 \quad \cdots \quad \phi_n^0]$; $\Lambda_r^0 = \mathrm{diag}(w_1^{02} \quad w_2^{02} \quad \ldots \quad w_r^{02}), r \le n$.

Mass matrix and stiffness matrix of structure determined by the parameter $b = [b_1 \quad b_2 \quad \ldots \quad b_n]$, its mass matrix and the stiffness matrix are a function of its structural parameters, where can be expressed as $M_B^0(b)$, $K_B^0(b)$.

Select the natural frequency close to the required frequency as constraints, therefore, use norm to represent the smallest of low-level modal difference as optimization criterion.

find

$$b$$

$$\min \sum_j \sqrt{\sum_i^n [\phi_j(i) - \phi_j^*(i)]^2}, \ j = 1,2,...,m,$$

$$s.t. \quad g_r(b) = \left| f_r - f_r^* \right| \le \eta f_r^* (r = 1,2,...,m), \tag{3}$$

$$b_l \le b \le b_u,$$

where, ϕ_j, f_r represents the vibration mode and natural frequency of designed wing structure; ϕ_j^*, f_r^* represents the vibration mode and natural frequency structure of the initial wings. m, N represents the modes of order and frequency of the order after modal truncation, and $m \le N$(this paper take $m=N$); η represents the error limit factor; b_l, b_u represents the upper and lower limit of conditional parameter in design structure. The result of the design showed in Figure 3.

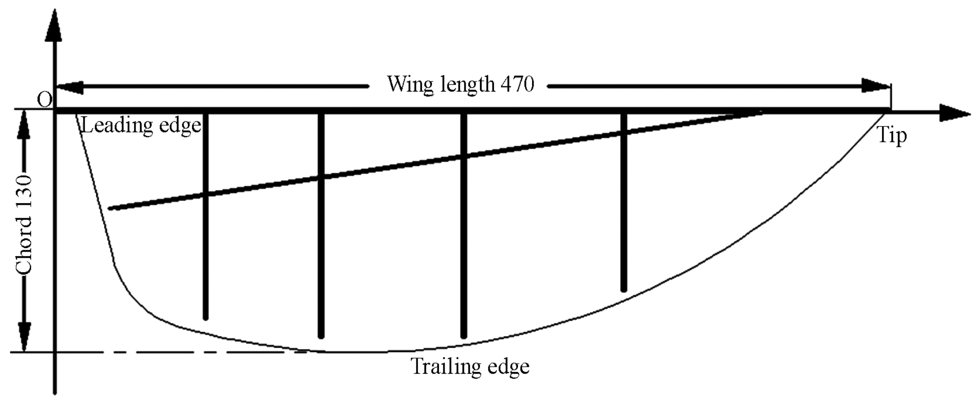

Figure 3
Structure and Shape of the Designed Wing

This structure and shape has a representative, similarly to a lot of natural insect wings's typical characteristics, such as mantis branch, most of stoneflies, orthoptera, hemiptera, etc. (Li, Fang, Hou, Fu, & Wu, 2005), which have a relatively flat, the good supported leading edge, good tact salient and soft to deformable easily rear edge . Such wings adapted to a wide range of reverse.

3. TAIL DESIGN OF FMAV

To select the tail of the program, it is necessary to select an airfoil, wing patterns and geometric parameters. On FMAV tail airfoil, the mainly airfoil used were bird-style wing, conventional-type tail (horizontal tail+tail) and v-tail. In the specific choice of tail airfoil, the impact on the stability and maneuverability, the methods of manipulation, the lift and drag characteristics and the weight, structural strength and other factors should consider. As long as the design is reasonable, different tail airfoil can provide sufficient stability and maneuverability the same in FMAV's flight, but the condition required in tail stability and maneuverability is not the same. For example, the imitation of the bird tail airfoil's shape usually triangular or sector, in the same area, compared with other tail airfoil, action point of aerodynamic is more rearward. If the installation point is the same, the tail arm of force will be longer, or in the case where the tail arm of force being equal, the length of the body may be small, which will reduce body weight. Conventional type and v-tail do not have the same advantages, but they can provide stability that crosses heading moment, this is their forte.

After a comprehensive comparison, the final selection in this paper is hirao airfoil tail, namely triangular flat frame plus film. This is mainly considered to meet the stringent requirements of the weight and reduce the designing of difficulty. Meanwhile, because of the lower flight speed, the loss of efficiency in use of hirao airfoil may not too much. The shape of hirao airfoil tail in Figure 4.

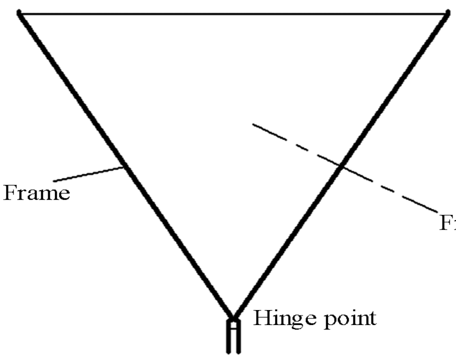

Figure 4
Design of Tail in FMAV

Parameters of design FMAV is closely associated with the wing of flapping characteristics the type of tail airfoil and the arrangement of tail, while the tail is a major component of the The whole vehicle, the parameters of the tail have a major impact on layout of aerodynamic shape. So parameters of the tail could not be a determined complete in one attempt, in general, it often need repeatedly try. After the initial setting, there need to estimate the whole vehicle's maneuverability, stability, and verification the experiment testing and then to do the further modifications. The design process of geometric parameters is shown in Figure 5.

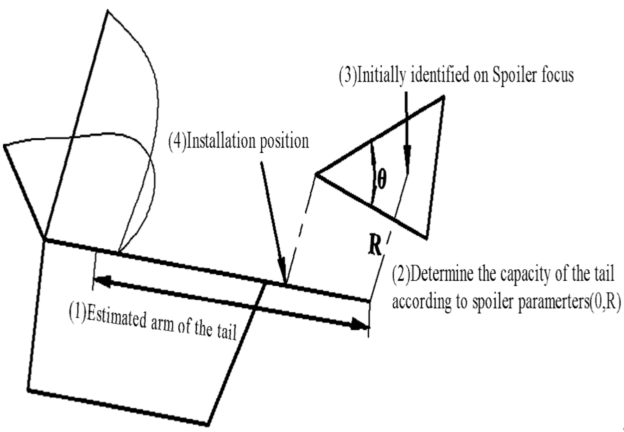

Figure 5
The Process of FMAV's Tail Geometry Design

As shown above, the selection of parameter generally began from longitudinal static stability, which is located behind the wing, caused the backward displacement of the pneumatic focal point of the whole vehicle is

$$\Delta\bar{x}_{ac} = \frac{C_{Lat}}{C_{La}}(1-\frac{\partial\varepsilon}{\partial\alpha})k_q A_{ht} \ . \tag{4}$$

As can be seen from Eqation 2, the tail capacity is the main parameters to determine the role of the hirao. In order to ensure that the aircraft has a longitudinal static stability, the pneumatic focus of whole vehicle located in a suitable position that behind the gravity center is required, so appropriate tail capacity is necessary to hirao.

Tail capacity of hirao is

$$A_{\mathrm{ht}} = \bar{S}_{ht}\bar{l}_{ht} = \frac{S_{ht}l_{ht}}{S_w c}. \tag{5}$$

Where, S_w—Vertical tail area，l_w—Vertical tail arm force, L—Wing span.

From the viewpoint of stability, static stability margin should have a positive value of sufficient size . Conventional aircraft generally require a static stability margin greater than 5%. For FMAV, due to the dynamic characteristics of vertical pitching motion, havr a higher requirements on static stability margin , where in this paper, take margin K_n as 15%.

To the lower limit of hirao tail capacity, because

$$K_n = \bar{x}_{acwb} + k_q A_{\mathrm{ht}}\frac{C_{Lat}}{C_{La}}(1-\frac{\partial\varepsilon}{\partial\alpha}) - \bar{x}_{cg} \, . \tag{6}$$

The required minimum tail capacity of hirao is

$$A_{\mathrm{ht}} = \frac{k_n + \bar{x}_{acwb} - \bar{x}_{cg}}{k_q \dfrac{C_{Lat}}{C_{La}}\left(1-\dfrac{\partial\varepsilon}{\partial\alpha}\right)}. \tag{7}$$

4. TRANSMISSION SYSTEM DESIGN OF FMAV

Transmission system of FMAV play the role of connection in energy transfer and wing flapping movement. Its function is to converts the motor rotational motion to wing flapping movement. Consider the case of the actual study, the lower weight and the higher driving torque, transmission system designing separated into two respects: the speed reducer and drive mechanism.

4.1 Speed Reducer System Design of FMAV

Integrated motor parameters and wing flapping frequency, consider the drive mechanism to overcome the rapidly changing in drive ratio. The final selection of speed reducer is three reducer system as shown in Figure 6 after several experimental test.

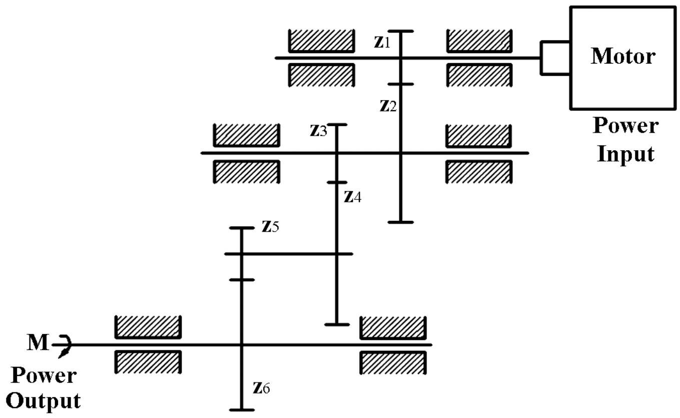

Figure 6
Three Gear Reducer System

Based on the transmission ratio and several verified tests, the parameters of gear reducer system is as showed in Table 2:

Table 2
Parameters of gear reducer system

Parameters	Value
Modulus	0.5
Pressure angle α	20º
Tooth number Z_1	6
Tooth number Z_2	16
Tooth number Z_3	10
Tooth number Z_4	16
Tooth number Z_5	8
Tooth number Z_6	20

4.2 Drive Mechanism Design of FMAV

Flapping wing flight differs from other methods is that it generates lift and thrust by flapping up and down, centralized hover, promote flight and steering in one system, so designed an efficient and reliable flapping wing drive mechanism is particularly important (Jiang, 2007)).

Flapping wing drive mechanism is usually composed by the rack, input rod, left and right wings of the rod and link members. The requirements of the designed drive mechanism are structured compact, small frictional resistance and to be able to achieve diverse complex movement like birds or insect. Figure 7 shows this paper's drive mechanism, frame is aircraft fuselage, input rod connecting the power source and wing flapping mechanism. Left and right wings of the rod flutter up and down to make the wings flapping. After gaining power, input rod driven other bars, generates the left and right wings flutter.

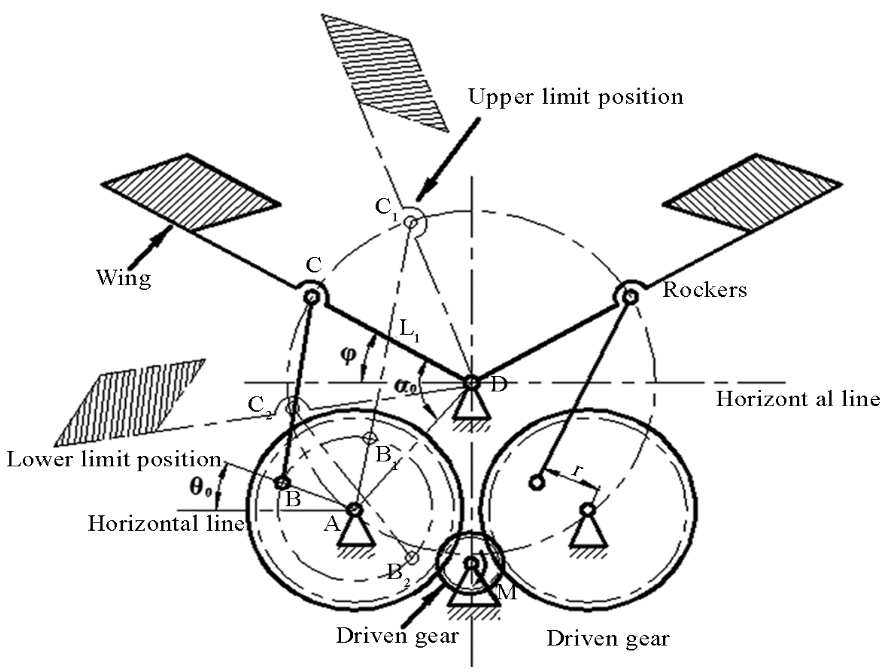

Figure 7
Drive Mechanism Schematic Diagram

Follower mechanism movement speed $\omega_2 = \frac{z_1}{z_2}\omega_1$ is point B's rotational speed. Reference the references (Sun, Chen, & Ge, 2006) to design the four-bar linkage composed by ABCD, the detail process is shown in Figure 8.

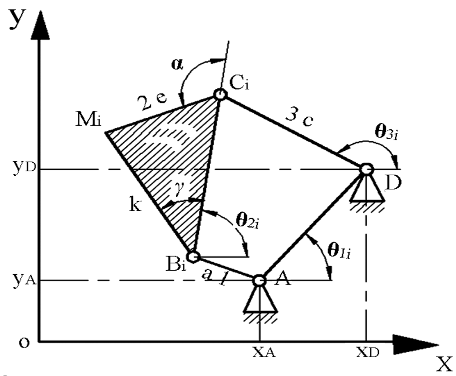

Figure 8
Four-Bar Linkage Design

As shown in Figure 8, because the planar motion of link, it can use an arbitrary choice of point (x_M, y_M) and azimuth of link θ_2 reprensentative the rod position. So in this paper, the design of connecting rod can be substituted by the design of the point M where the connecting rod occupy a series of predetermined positions $M_i(x_M, y_M)$ and the rotation angle θ_{2i}.

In order to simplify the design, separated the four-bar linkage into left and right sides to make discussion. Here established vector relationship of left side of the double-bar group

$$\vec{OA} + \vec{AB_i} + \vec{B_iM_i} - \vec{OM_i} = 0. \quad (8)$$

Axis projection in axis x and y

$$x_A + a\cos\theta_{1i} + k\cos(\gamma + \theta_{2i}) - x_{Mi} = 0, \quad (9)$$

$$y_A + a\sin\theta_{1i} + k\sin(\gamma + \theta_{2i}) - y_{Mi} = 0. \quad (10)$$

Eliminate θ_{1i} in formula (10), and then consolidation

$$\begin{gathered}(x_{Mi}-x_A)^2 + (y_{Mi}-y_A)^2 + k^2 - a^2 - 2\left[(x_{Mi}-x_A)k\cos\gamma + (y_{Mi}-y_A)k\sin\gamma\right]\cos\theta_{2i} \\ + 2\left[(x_{Mi}-x_A)k\sin\gamma - (y_{Mi}-y_A)k\cos\gamma\right]\sin\theta_{2i} = 0\end{gathered}. \quad (11)$$

Similarly, consolidation from the right of the double bar

$$\begin{gathered}(x_{Mi}-x_D)^2 + (y_{Mi}-y_D)^2 + e^2 - c^2 - 2\left[(y_{Mi}-y_D)e\sin\alpha - (x_{Mi}-x_D)e\cos\alpha\right]\cos\theta_{2i} \\ + 2\left[(x_{Mi}-x_D)e\sin\alpha + (y_{Mi}-y_D)e\cos\alpha\right]\sin\theta_{2i} = 0\end{gathered}. \quad (12)$$

Rocker's motion law of flapping wing flight is $\alpha = \alpha_0 + \frac{4}{5\pi}(\theta - \theta_i)$ (Christopher & Anouck, 2012), accurate solution by predetermined position of five-link, after rounding counted AB=10 mm, BC=36 mm, CD=16 mm, DA=16 mm, initial installation angle $\theta_1=\theta_2=35^0$.

So far, research FMAV test prototype has been completed, the whole vehicle figure shown as Figure 9 .

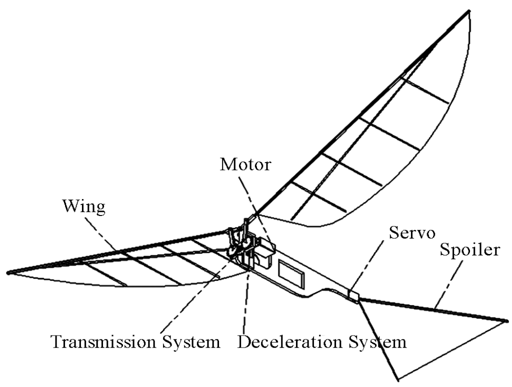

Figure 9
Schematic Diagram of Whole Vehicle

CONCLUSION

The process of FMAV experimental prototype designed from concept to the whole vehicle has been introduced in this paper. The designing of FMAV is separated into five parts: initial parameters setting, wing, tail and transmission system. The design of FMAV has provided a useful experience in the later design, and at the same time laid the foundation to subsequent wind tunnel tests and aerodynamic analysis.

REFERENCES

Michael, A. A., & Fenelon, T. F. (2010). Design of an active flapping wing mechanism and a micro aerial vehicle using a rotary actuator. *Mechanism and Machine Theory, 45*, 137-146.

Li, Z., Song, B., & Song, H. (2003). MAV research status and key technologies. *Journals of Flight mechanics journals, 21*(4), 1-4.

Hu, H., Kumar, G., Gregg, A., G., & Roberto, A. (2010). An experimental investigation on the aerodynamic performances of flexible membrane wings in flapping flight. Aerospace Science and Technology, 14, 575-586.

Tri Quang, T., Vu Hoang, P., Sanjay, P. S., Hoon, C. P. (2014). Pitching moment generation in an insect-mimicking flapping-wing system. J*ournal of Bionic Engineering, 11*, 36-51.

Taro, F., Kazuaki, H., Shinnosuke, O. (2008). Development of a small flapping robot motion analysis during take off by numerical simulation and experiment. *Mechanical Systems and Signal Processing, 22,* 1304-1315.

Albertani, R., Stanford, B., Hubner, J. P., & Ifju, P. G. (2007). Aerodynamic coefficients and deformation measurements on flexible micro air vehicle wings. *Experimental Mechanics, 47,* 625-635.

Sanjay, P. S. (2006). The aerodynamics of insect flight. *Journal of Experimental Biology,* 4191-4208.

Wei, S., Mats Bergand, D. L. (1999). Happingand flexible wings for biological and micro air vehicles. *Progress in Aerospace Sciences*, (35), 455-505.

Liu, L., Fang, Z., Hou, Y., & Wu, L. (2005). Bionic design and scaling laws for flapping- wing MAV. *China Mechanical Engineering, 16*(18), 1613-1616.

Chen, Z., Weng, P., & Ding, Y. (2013). Aerodynamic analysis on zimmerman and inverse zimmerman wings of miniature air vehicle. *Journal of Shanghai University (Natural Science), 19*(1), 80-85.

Li, L., Fang, Z., Hou, Y., Fu, W., & Wu, L. (2005). Aerodynamic modeling and experimental analysis of FMA.*Journal of Aerospace Power, 20*(1), 22-28.

Jiang, J. (2007). Flapping-wing mechanism design of FMAV and its dynamic simulation and analysis. *Southwest Jiaotong University,* 48-64.

Sun, H., Chen, Z.，& Ge, W. (2006). Mechanical principles. *Northwestern Polytechnical University,* 121-132.

Christopher, T. O., & Anouck, R. G. (2012). Dynamics, stability, and control analyses of flapping wing micro-air vehicles. *Progress in Aerospace Sciences, 51*, 18-30.