The Hybrid Bio-Inspired Aerial Vehicle: Concept and SIMSCAPE Flight Simulation

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Abstract— **This paper introduces a Silver Gull-inspired hybrid aerial vehicle, the Super Sydney Silver Gull (SSSG), which is able to vary its structure, under different manoeuvre requirements, to implement three flight modes: the flapping wing flight, the fixed wing flight, and the quadcopter flight (the rotary wing flight of Unmanned Air Vehicle). Specifically, through proper mechanism design and flight mode transition, the SSSG can imitate the Silver Gull's flight gesture during flapping flight, save power consuming by switching to the fixed wing flight mode during long-range cruising, and hover at targeted area when transferring to quadcopter flight mode. Based on the aerodynamic models, the Simscape, a product of MathWorks, is used to simulate and analyse the performance of the SSSG's flight modes. The entity simulation results indicate that the created SSSG's 3D model is feasible and ready to be manufactured for further flight tests.**

I. INTRODUCTION

The Unmanned Aerial vehicles (UAV) family has three main flight types, the fixed wing, flapping wing and rotary wing. There have been some types of wings' combinations and configurations in both of the academic research and industrial applications of UAVs. According to the available literatures, heretofore, the hybrid UAVs were all designed based on the fixed wings and rotors without exception [1], [2], [3], [4]. The above representative Hybrid UAVs are differ due to whether the rotors and wings tilted or fixed during their flight mode conversions.

As a further step of the Hybrid UAVs, this paper proposed a bird size hybrid aerial vehicle named Super Sydney Silver Gull (SSSG). SSSG is able to perform three flight modes: accurate hovering, energy efficient cruising, and bird-mimicking flapping flight, which possesses the advantages of stable flight, easier control, long time endurance and considerable payload saving. One of the purposes of design the SSSG is for the monitoring of the shark activity along the New South Wale's coastal beach in order to minimize the risk of shark attacking.

II. MECHANICAL IMPLEMENTATION

The designed SSSG is based on the platform of Silver Gull inspired flapping wing aerial vehicles [5]. The platform has a body length about 450 mm, wingspan about 1000 mm and aspect ratio about 10.

The wing of the flapping mechanism is made up of two parts, the primary wings and the secondary wings. During the upstroke phase, the secondary wings move with the primary wings' main movement and fold gradually until the main movement reach its upper limit. Similarly, during the downstroke phase, the secondary wings unfold from upper limit to lower limit with their interaction angles changed opposite to the upstroke phase. For more information about the applied mechanisms, please see [6]. In order to obtain optimized aerodynamic performance, the wing shape S1223 high lift low Reynolds number airfoil, which is most similar to Silver Gull's wing shape, is selected according to [7].

The fixed wing cruising flight of SSSG is achieved by fix the wings horizontally and driven by the rotor mounted at the front of the wings. Located between the wings and the head, the propeller is driven by the motor through speed reduction gear set. The paddles of the propeller are designed into two parts, each of them is revolving assembled to the joint of the passive rotated internal gear. Due to the integrated effect of air flow, gravity and centrifugal force, the paddles of the propeller will attach to the surface of the body during forward flapping flight and swing to the parallel orientation of the internal gear at fixed wing cruising mode.

The quadcopter flight of SSSG, is implemented by four motor driven propellers. Mounted symmetric about the central body of SSSG, the motors and propellers is located in the body of the SSSG and stretch to the outer space at the quadcopter mode only. At the quadcopter mode, the primary wings remain at the upper limit position meanwhile the associated secondary wings parallel to the body plane so as to make space for the four propellers to generate aerodynamic forces and avoid air flow interaction between the quadcopter and fixed wing.

III. MODELLING

A. MATHEMATICAL MODEL

The geometry and reference frames of the designed SSSG are shown in Figure 1. Although the mass of the head and tail can be adjusted for the flight control purpose, they are assumed to be part of the body and have no relative motion with respect to it. So in this paper, *body* means the integration of the head, tail and the central body. The body, as the main research object, has six degrees of freedom (DOF), ie. three translational motion (forward and backward, left and right, up and down) and three rotational motion (roll, pitch and yaw).

There are two basic reference frames in the system, the inertial frame denoted as f_E and the body fixed frame f_b. The earth fixed frame f_E (x_E, y_E, z_E) follows the right hand rule, which defines the position of the SSSG with its

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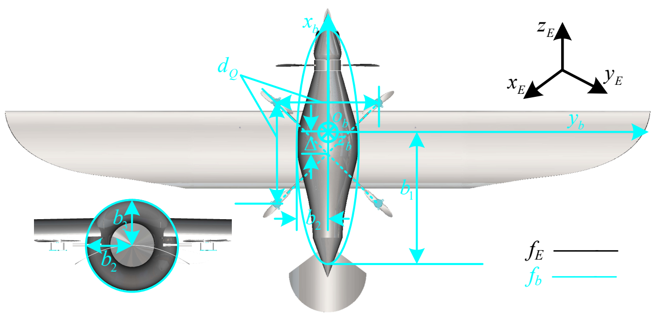

Fig. 1. Geometry and Reference Frames of the designed Hybrid SSSG

positive coordinates x_E, y_E and z_E points due north, due east and directly downward, respectively. All of the other orthogonal coordinate systems in this paper also follow the right hand rule. The body fixed frame $f_b(x_b,y_b,z_b)$ is defined with its origin O_b at the center of mass of the body, while O_b is represented as O_{b1}, O_{b2} and O_{b3} at fixed, flapping and quadcopter wing mode, respectively. The shape of the modelled body can be approximated by an ellipsoid and the length, width and height of the body should be $2b_1$, $2b_2$ and $2b_3$ respectively. The total mass and gravity of SSSG are defined as m and G. The inertial matrix about the O_b is given by I_b. The body is always symmetric to the plane of $x_b z_b$.

Euler angles ψ, θ and ϕ are defined to describe the rotation from f_E to f_b, while R_E^b is defined as the rotation matrix. The Euler angle ψ describes the yaw motion of the body, which rotates about the z_b axis and with a positive direction from North to East. θ describes the pitch motion of the body, which rotates about the y_b axis and with a positive direction of head-up. ϕ describes the roll motion of the body, which rotates about the x_b axis and regards as positive when the body made the right wing down but left wing up. The orientation of the body with respect to the inertial frame is defined by the 3-2-1 Euler angles rotation [8]. The equations of motion of the SSSG at fixed wing mode can be obtained by referring to the conventional standard aircraft [9]

$$
\begin{aligned}
&\begin{bmatrix} \dot{x}_E \\ \dot{y}_E \\ \dot{z}_E \end{bmatrix} = {R_E^b}^{-1} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = {R_E^b}^{T} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}, \\
&\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -s_\theta \\ 0 & c_\phi & c_\theta s_\phi \\ 0 & -s_\phi & c_\theta c_\phi \end{bmatrix}^{-1} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}, \\
&\begin{bmatrix} \dot{v}_x \\ \dot{v}_y \\ \dot{v}_z \end{bmatrix} = \frac{1}{m_b} \begin{bmatrix} F_x - G s_\theta \\ F_y + G c_\theta s_\phi \\ F_z + G c_\theta c_\phi \end{bmatrix} + \begin{bmatrix} \omega_z v_y - \omega_y v_z \\ \omega_x v_z - \omega_z v_x \\ \omega_y v_x - \omega_x v_y \end{bmatrix}, \\
&\begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} = I_b^{-1} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} + I_b^{-1} \omega_b \times I_b \omega_b,
\end{aligned}
\tag{1}
$$

where s_θ, $v_x, v_y, v_z, \omega_x, \omega_y$, ω_z, F_x, F_y, F_z, M_x, M_y and M_z represent $sin\theta$, translational and rotational velocity, aerodynamic forces and moments act on the center of mass of SSSG, x_b, y_b and z_b, respectively.

1) FIXED WING FLIGHT: At the fixed wing flight mode, (1) is eligible to be used for the flight simulation which is widely applied on the conventional airplanes. As shown in the first row of Figure 2, the wings hold at the horizontal position and the flight power is from the propeller which driven by the motor mounted between the wings and the head. Assuming the fixed wing phase SSSG can reach a cruising speed of 9.5 m/s (according to the data from [10])with the angle of attack (AOA) at about 2° to 5°. The Reynolds number can be calculate from

$$
\begin{aligned}
Re &= \rho v l/\mu = v l/\nu \\
&= (9.5m/s \cdot 0.1m)/1.4207 \cdot 10^{-5} m^2/s = 66,868.
\end{aligned}
\tag{2}
$$

Referring to the data of the selected high lift low Reynolds number airfoil S1223 [11], [12], find the C_L is between 1.10 and 1.20 by obtain the relationship of its lift coefficient (C_L) characteristic refer to the AOA around the Reynolds number between 60,000 to 80,000. The generated aerodynamic lift by the cruising flight of the fixed wings can be calculated from

$$L_1 = \sum L_{1i} = 1/2 C_L \rho v^2 S, \tag{3}$$

where C_L is between 1.10 and 1.20, ρ= 1.29 kg/m^3 is the density of the air, S is the projected area of the wings at a certain AOA. According to the correspondence relationship of the AOA and C_L, L_1 is between 6.31 N and 6.87 N at a cruising velocity of 9.5 m/s, which means the generated aerodynamic lift forces can support the gravity of the SSSG which is designed to have a total mass of about 650 g. The aerodynamic thrust can be presented by

$$T_1 = \sum T_{1i} = c_{T1} {\omega_1}^2, \tag{4}$$

where c_{T1} is a constant which can be determined by real prototype static thrust test, and ω_1 is the rotation velocity of the rotor. So F_x and F_z can be presented as

$$F_x = T_1, \tag{5}$$
$$F_z = L_1 - G. \tag{6}$$

The center of gravity O_{b1} can be adjusted so as to get $M_y = 0$. Due to its geometry symmetric to the $x_b z_b$ plane, F_y, M_x and M_z are zero.

2) FLAPPING WING FLIGHT: The center of gravity of the flapping wing changed with flapping motion, while introducing some hypothesis and simplifications on the derivation of multi rigid bodies equations of motion cannot accurately present the motion of the SSSG. The physical simulation method in SIMSCAPE/SIMULINK environment is used in this case. The aerodynamic forces and moments that are generated during flapping flight can be referred to [13] with its supplementary supporting materials. The lift force, thrust

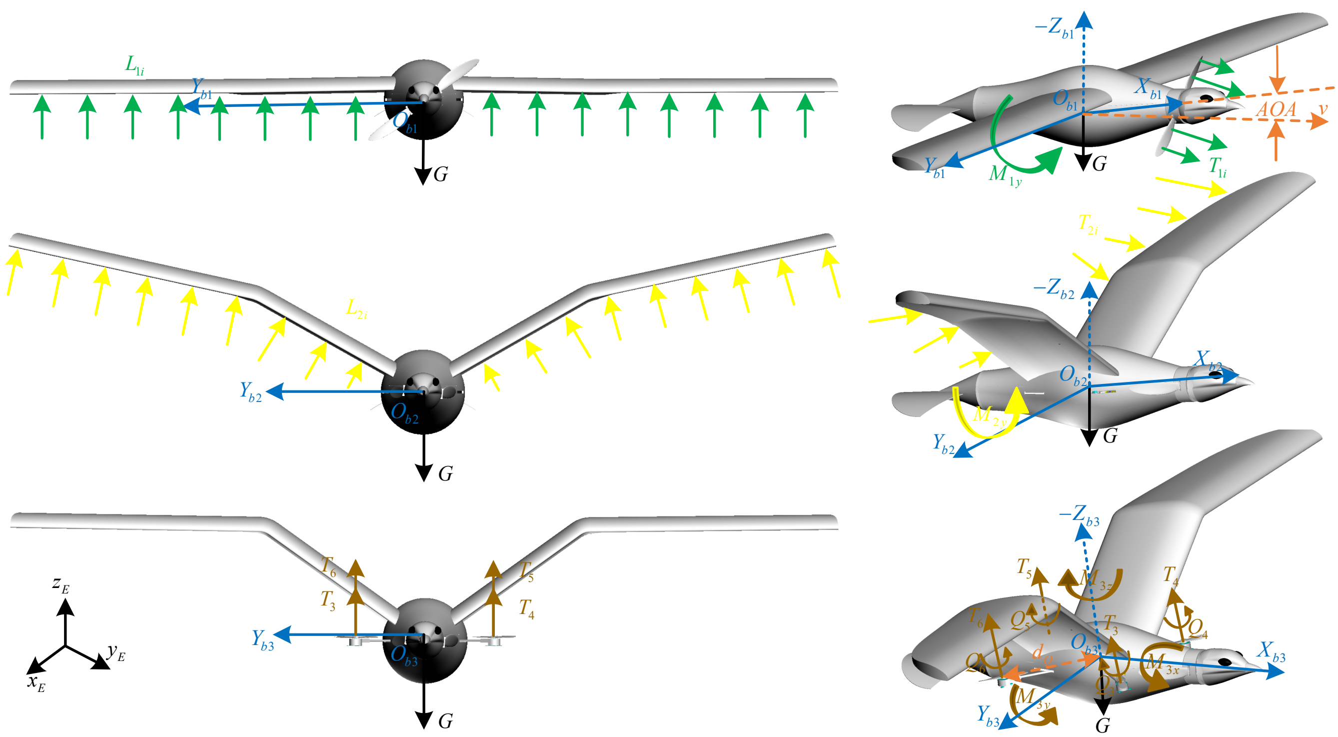

Fig. 2. Aerodynamic forces and moments at three flight modes, from top to bottom are fixed wing, flapping wing and quadcopter flight mode respectively

force and pitching moment can be calculated by

$$L_2 = \pi A A_1 \left(\alpha_0 - \frac{4}{\pi} I_{11} \alpha_1 \right), \tag{7}$$

$$T_2 = \dot{W} - D_i, \tag{8}$$

$$\begin{aligned} M_y = {} & 4A(\dot{h}\phi + \lambda) \left(\alpha_0 A_1 I_{11} - \frac{4}{\pi} \alpha_1 K_1 \right) \\ & + \frac{4}{\pi} A \phi \dot{\phi} \left(\alpha_0 A_1 - \frac{4}{\pi} \alpha_1 (A_1 I_{11} + A_3 I_{13}) \right) \\ & + 4\phi {\alpha_0}^2 A {A_1}^2 I_{11} - \frac{8}{\pi} \alpha_0 \alpha_1 \phi A A_1 K_4 + \frac{32}{\pi^2} A \phi K_5, \end{aligned} \tag{9}$$

where

$$\begin{aligned} \dot{W} = {} & -4AA_1 I_{11} \alpha_0 \dot{\phi} + \frac{16}{\pi} A K_1 \alpha_1 \dot{\phi} \\ & -\pi A A_1 \alpha_0 \dot{h} + 4AA_1 I_{11} \alpha_1 \dot{h}, \end{aligned} \tag{10}$$

$$D_i = \pi A {A_1}^2 {\alpha_0}^2 - 8A{A_1}^2 I_{11} \alpha_0 \alpha_1 + A\frac{16}{\pi} K_2 {\alpha_1}^2, \tag{11}$$

A is the aspect ratio, A_1, A_2... are functions of the aspect ratio defined by

$$A_n = \frac{2}{A + 2n}, \tag{12}$$

$\alpha, \alpha_0, \alpha_1$ represent the angle of attack, its value at the root and its increase along the span, I_{11}=-1/3, I_{13}=-1/5 is the standard integrals, h represent the vertical displacement of the wing's root from a straight path, ϕ is the flapping angle, λ is the sweep angle and is zero in our research, K_1, K_2... et. al are the function of the aspect ratio. F_y, M_x and M_z are all zero due to the geometry and motion be symmetric about the $x_b z_b$ plane.

3) QUADCOPTER WING FLIGHT: The SSSG can be regard as one rigid body and both of the mathematical (1) and SimMechanics model can be used to describe the hovering flight of the SSSG. Define the rotors sequence as 3, 4, 5 and 6, as shown in the third row of Figure 2. During hovering flight, referring to [14], the thrust force T_i, torque moment Q_i of rotor i (i=3, 4, 5, 6) with respect to O_{b3} can be presented as

$$T_i = c_{T2} {\omega_i}^2, \tag{13}$$

$$Q_i = c_Q {\omega_i}^2 \tag{14}$$

where c_{T2} and c_Q are constants and can be determined by static thrust tests. Total aerodynamic thrust forces and moments can be presented as T_{quad} and τ_x, τ_y and τ_z respectively, where

$$T_{quad} = c_{T2} \left({\omega_3}^2 + {\omega_4}^2 + {\omega_5}^2 + {\omega_6}^2 \right), \tag{15}$$

$$\tau_x = \frac{1}{2} d_Q c_{T2} \left(-{\omega_3}^2 + {\omega_4}^2 + {\omega_5}^2 - {\omega_6}^2 \right), \tag{16}$$

$$\begin{aligned} \tau_y = {} & \frac{1}{2} d_Q c_{T2} \left({\omega_3}^2 + {\omega_4}^2 - {\omega_5}^2 - {\omega_6}^2 \right) \\ & - c_{T2} \Delta \left({\omega_3}^2 + {\omega_4}^2 + {\omega_5}^2 + {\omega_6}^2 \right), \end{aligned} \tag{17}$$

$$\begin{aligned} \tau_z = {} & c_Q \left({\omega_3}^2 - {\omega_4}^2 \right) \sqrt{ \frac{1}{2} {d_Q}^2 + \left(\frac{1}{2} d_Q - \Delta \right)^2 } \\ & + c_Q \left({\omega_5}^2 - {\omega_6}^2 \right) \sqrt{ \frac{1}{2} {d_Q}^2 + \left(\frac{1}{2} d_Q + \Delta \right)^2 }, \end{aligned} \tag{18}$$

d_Q and Δ represent distances of rotor i (i=3, 4, 5, 6) between each other and offset between the geometric centre of the four rotors and O_b respectively, as shown in Figure 1. At the

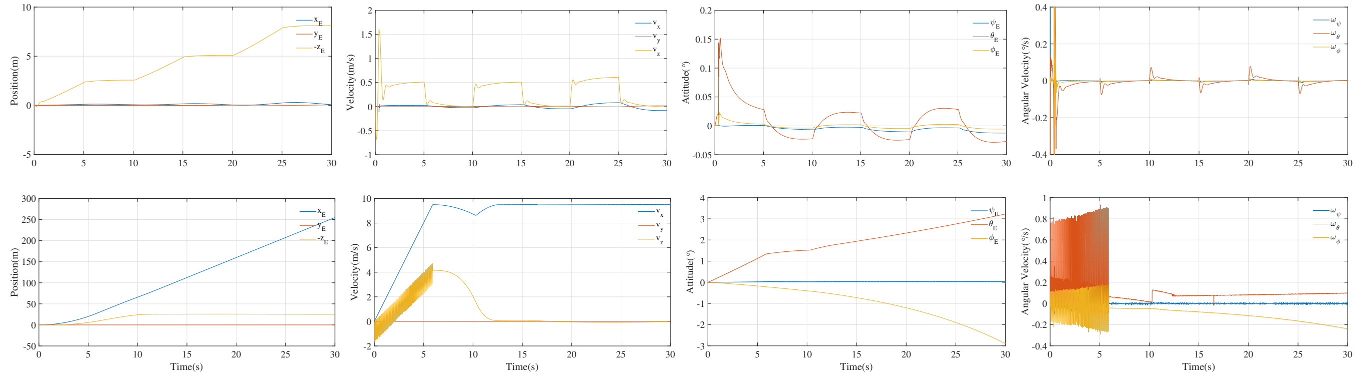

Fig. 3. This group of figures demonstrate flight simulation results of the SSSG at different flight modes. Horizontally, from the left column to the right, the figures describe its position, velocity, attitude and angular velocity, respectively. Vertically, from the first row to the second, the figures presented the above four flight parameters at quadcopter wing and hybrid wing flight modes, respectively.

hovering mode, the SSSG has no translational and rotational movement, thus we obtain

$$F_{3x} = F_{3y} = F_{3z} = T_{quad} - G = 0, \tag{19}$$

$$M_{3x} = \tau_x = M_{3y} = \tau_y = M_{3z} = \tau_z = 0 \tag{20}$$

B. *SIMMECHANICS MODEL*

In this paper, the designed SSSG is simulated in Simulink SimMechanics. Globally gravity (0, 0, -9.81) m/s^2 and six sensors $(x, y, z, \phi, \theta, \psi)$ are implemented so as to simulate the real flight and measure the targeted real-time position and orientation for simulation and control purposes.

The mass property of the whole SSSG model including the payload is around 650g. The center of gravity can be adjusted by changing the relative position of payloads.

IV. SIMULATION

Selected cases are simulated and discussed, including the quadcopter and combined flight.

At the quadcopter flight mode, based on the closed-loop feed-back controller, the SSSG is designed to hover at certain time interval and then changed to another altitude with its attitude being controlled. For instance, the quadcopter SSSG first take off from 0 m to 2.5 m, during which the velocity v_z increased to about 0.5 m/s and then dropped to 0 m/s during the following 5 seconds for hovering. Apart from the vertical controlled flight, the quadcopter SSSG is hovering during the rest of the time interval from 0 s to 30 s, as shown in the first row of Figure 3.

The combined flight simulation from flapping flight taking off to fixed wing cruising is shown in the last row of Figure 3. The flight is designed to transit from flapping flight to fixed wing flight. As can be find from the variation of velocity and angular velocity, after the SSSG reach its velocity v_x equals to 9.5 m/s at about 5.9 s, the transition started with its velocity v_x and v_z are controlled at about 9.5 m/s and 0 m/s, respectively.

V. CONCLUSION AND FUTURE WORK

In this paper, a hybrid UAV, SSSG, has been proposed, designed and simulated by combining the mathematical aerodynamic models and SimMechanics based simulation. It has been demonstrated SSSG can perform flapping, cruising, and hovering at different modes. In addition, the altitude and attitude control in quadcopter flight modes are successfully implemented and tested in SimMechanics simulation. The consecutive flight from taking off by flapping flight to target area by quadcopter flight will be investigated. The SSSG prototype and its real flight test is also the future work to validate this project.

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