Dynamics Modeing and Maneuverability Analysis of a Near-Space Earth Observation Platform

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Abstract—**Near-space autonomous airship represents a unique and promising platform for earth observation and surveillance that involve a long duration airborne presence. In this paper, a six-degrees-of-freedom dynamics model and maneuverability of a near-space earth observation platform are presented. First, the near-space earth observation platform is introduced, including the concept design, configuration, energy sources, propeller and payload. Second, reference frames and motion parameters of the platform are defined, and the kinematics equations describing the platform's dimensional motion are derived. The effects of gravity, buoyancy, added inertia, aerodynamics and thrust on the platform are incorporated into the dynamics analysis, and a dynamics model in vector form of the platform is derived based on Newton-Euler principle. Finally, a simulation program has been developed to implement the dynamics model and applied to analyze the maneuverability of the platform. It is hoped that this work is useful to support the evaluation of maneuverability and the development of control system for the near-space earth observation platform.**

Keywords-dynamics modeling; maneuverability; Newton-Euler principle; earth observation platform; near space;

I. INTRODUCTION

Near-space is quantitatively defined as the range of earth altitudes from 20 km to 100 km, below which commercial aircraft can produce sufficient lift for steady flight and above which the atmosphere is rarefied enough for satellites to orbit with meaningful lifetimes [1]. There has been recent interest in near-space long duration vehicles motivated by the possibility of operating such vehicles with the relative benefits of both high-altitude aircrafts and low-altitude satellites [2]. The autonomous airship is a type of lighter-than-air vehicle that can be operated in near-space with some payloads and other durable systems, and is considered as a new platform that will support a great many missions such as telecommunication, broadcasting relays, region navigation, earth observation and surveillance.

The near-space airship platform has several advantages over satellites and conventional planes: compared with satellites, it is highly cost-effective, very mobile, fast to deploy and convenient to retrieve; compared with conventional planes, it has extraordinary advantages such as long duration, wide coverage, station-keeping and great survivability [3]. The growing worldwide interests in the study on the near-space airship platform create a need for accurate dynamics model to analyze its maneuverability and flight behavior. In this paper, a concept design of a near-space earth observation platform is discussed. A six-degrees-of-freedom (6DOF) dynamics model of the platform is presented based on Newton-Euler principle, with a particular focus on a comprehensive formulation of the added mass and inertia, gravity, buoyancy, aerodynamics and thrust on the platform. A simulation program based on the dynamics model is developed and applied to analyze the maneuverability of the platform. The remainder of this paper is organized as follows. Section 2 presents a concept design of the near-space earth observation platform. Section 3 derives the kinematics and dynamics equations of the platform. Simulation results and maneuverability of the platform is presented in Section 4.

II. CONCEPT DESIGN

The near-space earth observation platform is required to have a capability of station-keeping at an altitude of approximately 20 km, and to have a long duration airborne presence of several years, under a design wind speed of 20m/s. Lighter-than-air airships represent a unique and promising solution for this requirement, which have exceptionally long endurance and autonomy. As shown in Fig. 1, the airship platform consists of an axis-symmetric, teardrop-shaped hull with solar power cells, propellers, tail fins, gondola and payload.

The hull is composed of an air-pressurized envelope to maintain its shape, and internal divided bags filled with helium as a buoyant gas. Two air ballonets are installed inside the hull, which are controlled by a common pneumatic system of pipes and valves. These ballonets can be blown up with air and deflated, respectively during the descent and climb operations, in order to handle altitude variations without losing helium from the hull and avoiding any significant change in the hull shape. The electric power is available from solar cells distributed to the propulsive motors, the flight control system and the payload mission. Propulsive propellers are mounted on

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the larboard, starboard and stern of the platform, and four tail fins of "+" shape are installed on the rear end of the hull as control surface. The payload including optical cameras and other imaging equipments can accomplish missions such as station-keeping surveillance and reconnaissance.

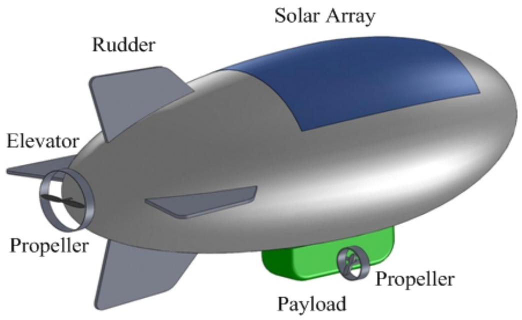

Figure 1. Sketch of the earth observation platform

III. DYNAMICS MODELING

A. Kinematics equations

When analyzing the motion of the platform in 6 DOF it is convenient to define two reference frames. These are the body-fixed reference frame B(oxyz) and the earth-fixed reference frame E(OXYZ) [4], as shown in Fig. 2. The B frame is conveniently fixed to the platform. The origin o of B frame is usually chosen to coincide with the centre of volume (CV), the x-axis along the hull centerline and pointing toward, the z-axis vertically downward and the positive y-axis determined by the right hand rule. The E frame is an earth-fixed inertial frame, with the origin O on the earth. The Z-axis points to the center of the earth, the X-axis points in some arbitrary direction, e.g. the north, and the Y-axis is perpendicular to the X-axis.

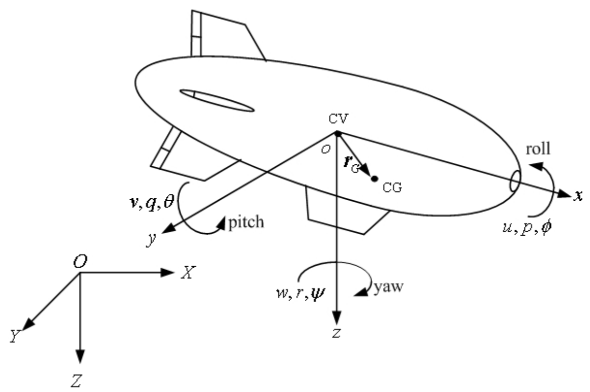

Figure 2. Reference frames and motion parameters of the platform

In order to describe the motion of the platform in 6 DOF, six independent coordinates representing position and attitude are necessary. The platform kinematics can be described by its position, orientation, velocity and angular velocity over time. The position vector is given by $\boldsymbol{P} = [x, y, z]^T$ in the E frame, with x pointing to true north, y pointing east, and z pointing downward. Velocities are described in the B frame with linear velocity $\boldsymbol{v} = [u, v, w]^T$, where u is the longitudinal velocity, v is the lateral velocity and w is the vertical velocity. The attitude is described by Euler angles $\boldsymbol{\Omega} = [\theta, \psi, \phi]^T$, with pitch angle θ, roll angle ϕ, and yaw angle ψ. The angular velocity vector is given by $\boldsymbol{\omega} = [p, q, r]^T$, where p, q and r is the roll, pitch and yaw angular velocity, respectively.

The kinematics equations of the platform can be expressed as follows:

$$\begin{bmatrix} \dot{\boldsymbol{P}} \\ \dot{\boldsymbol{\Omega}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{S}_1 & 0_{3\times3} \\ 0_{3\times3} & \boldsymbol{S}_2 \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix} \tag{1}$$

using the rotation matrix

$$\boldsymbol{S}_1 = \begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{2}$$

and the kinematics transformation matrix

$$\boldsymbol{S}_2 = \begin{bmatrix} 0 & \cos\phi & -\sin\phi \\ 0 & \sec\theta\sin\phi & \sec\theta\cos\phi \\ 1 & \tan\theta\sin\phi & \tan\theta\cos\phi \end{bmatrix} \tag{3}$$

B. Dynamics equations

In the attempt to establish a workable dynamics model of the platform, for practical reasons a number of assumptions have to be taken into account:

1. The platform is assumed to be a rigid body, and the aero-elastic effects are ignored.

2. The earth is flat and non-rotating, and the earth-fixed reference frame is regarded as an inertial reference frame.

3. The mass is constant during the time interval over which the motion is considered, the helium leak is neglected during this time interval.

4. The center of volume and the center of gravity lie in the plane of symmetry, and the center of the volume coincides with the gross center of buoyancy.

5. The mass distribution of the platform is symmetric relative to the xoz plane, this implies that the products of inertial I_{xy} and I_{yz} are equal to zero.

The dynamics equations of the platform can be derived from Newton-Euler principle, which can be expressed by two vector equations in the E frame as follow [5]:

$$\boldsymbol{F} = \left.\frac{d(m\boldsymbol{v})}{dt}\right|_E \tag{4}$$

$$\boldsymbol{\tau} = \left.\frac{d\boldsymbol{H}}{dt}\right|_E \tag{5}$$

where $\boldsymbol{F}$ represents the sum of all externally applied forces, m is the mass of the platform, $\boldsymbol{v}$ is the velocity vector, $\boldsymbol{\tau}$ represents the sum of all applied torques and $\boldsymbol{H}$ is the angular momentum.

By using the Newton-Euler formulation, the 6-DOF dynamics model of the platform with respect to the B frame with origin o can be stated as:

$$m[\dot{\boldsymbol{v}}+\boldsymbol{\omega}\times\boldsymbol{v}+\dot{\boldsymbol{\omega}}\times\boldsymbol{r}_G+\boldsymbol{\omega}\times(\boldsymbol{\omega}\times r_G)]=\boldsymbol{F} \tag{6}$$

$$\boldsymbol{I}_0\dot{\boldsymbol{\omega}}+\boldsymbol{\omega}\times(I_0\boldsymbol{\omega})+m\boldsymbol{r}_G\times(\dot{\boldsymbol{v}}+\boldsymbol{\omega}\times\boldsymbol{v})=\boldsymbol{\tau} \tag{7}$$

where $\boldsymbol{r}_G=[x_G,y_G,z_G]^T$ is the distance vector from CV to CG and $\boldsymbol{I}_0$ is the inertia tensor with respect to the origin o of the B frame, that is:

$$\boldsymbol{I}_0=\begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{yx} & I_y & -I_{yz} \\ -I_{zx} & -I_{xy} & I_z \end{bmatrix}$$

Here I_x , I_y and I_z are the moments of inertia about ox , oy and oz axis, and $I_{xy}=I_{yx}$, $I_{xz}=I_{zx}$ and $I_{yz}=I_{zy}$ are the product of inertia.

Any body moving through a fluid displaces that fluid. This displacement contributes to the overall change in momentum of the vehicle. For an airship platform with large volume and inertia, it is necessary to account for the linear and angular momentum of the air in the dynamics model. It results in "added mass" and "added inertia" terms added to the nominal mass and inertia of the platform [6]. The general form of the 6 DOF dynamics equations for the platform can be expressed as follows [7]:

$$\begin{bmatrix} m\boldsymbol{E}+\boldsymbol{M}_a & -m\boldsymbol{r}_G^{\times} \\ m\boldsymbol{r}_G^{\times} & \boldsymbol{I}+\boldsymbol{I}_a \end{bmatrix}\begin{bmatrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix}+\begin{bmatrix} m(\boldsymbol{\omega}\times\boldsymbol{v}+\boldsymbol{\omega}\times(\boldsymbol{\omega}\times\boldsymbol{r}_G)) \\ \boldsymbol{\omega}\times(\boldsymbol{I}\boldsymbol{\omega})+m\boldsymbol{r}_G\times(\boldsymbol{\omega}\times\boldsymbol{v}) \end{bmatrix}=\begin{bmatrix} \boldsymbol{F} \\ \boldsymbol{\tau} \end{bmatrix} \tag{8}$$

where $\boldsymbol{E}$ is the 3×3 identity matrix, $\boldsymbol{M}_a$ is the added mass matrix, $\boldsymbol{I}_a$ is the added inertial matrix[7], $\boldsymbol{r}_G^{\times}$ is the skew symmetric matrix of $\boldsymbol{r}_G$, $\boldsymbol{F}$ and $\boldsymbol{\tau}$ represent aerodynamic forces and moments, buoyancy, gravity and propulsive thrust.

In the B frame, the aerodynamic force and moment on the platform surface can be expressed as follows:

$$\boldsymbol{F}_A=\boldsymbol{S}_3\begin{bmatrix} -Q\mathrm{V}^{2/3}C_D \\ Q\mathrm{V}^{2/3}C_Y \\ -Q\mathrm{V}^{2/3}C_L \end{bmatrix},\ \boldsymbol{\tau}_A=\begin{bmatrix} Q\mathrm{V}C_l \\ Q\mathrm{V}C_m \\ Q\mathrm{V}C_n \end{bmatrix}$$

where $\boldsymbol{S}_3$ is the rotation matrix changing form the wind coordinate frame to the body coordinate frame [4], V is the platform volume, Q is the dynamic pressure, C_D , C_Y , C_L , C_l , C_m and C_n are the non-dimensional coefficients of drag force, side force, lift force, roll moment, pitch moment and yaw moment, respectively.

In the B frame, the gravity force and moment can be expressed as follows:

$$\boldsymbol{F}_G=\begin{bmatrix} -G\sin\theta \\ G\cos\theta\sin\phi \\ G\cos\theta\cos\phi \end{bmatrix},\ \boldsymbol{\tau}_G=\begin{bmatrix} y_G G\cos\theta\cos\phi-z_G G\cos\theta\sin\phi \\ -z_G G\sin\theta-x_G G\cos\theta\cos\phi \\ x_G G\cos\theta\sin\phi+y_G G\sin\theta \end{bmatrix}$$

where G is the gravity of the platform.

In the B frame, the buoyancy force and moment can be expressed as follows:

$$\boldsymbol{F}_B=\begin{bmatrix} B\sin\theta \\ -B\cos\theta\sin\phi \\ -B\cos\theta\cos\phi \end{bmatrix},\ \boldsymbol{\tau}_B=\begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T$$

The propulsive force and moment acted by the airscrew propellers can be expressed as follows:

$$\boldsymbol{F}_T=\begin{bmatrix} T\cos\mu \\ T\sin\mu \\ 0 \end{bmatrix},\ \boldsymbol{\tau}_T=\begin{bmatrix} T\cos\mu\cdot l_z \\ T\sin\mu\cdot l_x-T\cos\mu\cdot l_y \\ T\sin\mu\cdot l_z \end{bmatrix}$$

where μ is the deflective angle of propeller in left-right direction, l_x , l_y and l_z are the coordinates of propeller relative to the center of volume.

IV. MANEUVERABILITY ANALYSIS

A simulation program has been developed in the MATLAB environment to implement the nonlinear dynamics model discussed above. In the numerical simulation, a designed airship was used as an example, since the dimensional and inertial parameters were available for the platform, as shown in Table 1.

Table 1 Airship Parameters Value

parameter	value	parameter	value
m	61800 kg	ρ_{air}	0.089 kg/m^3
V	6.9×10^5m^3	I_x	0.98×10^7 kgm^2
I_y	5.12×10^9 kgm^2	I_z	5.09×10^9 kgm^2
I_{xy}	0 kgm^2	I_{xz}	1.04×10^6 kgm^2
I_{yz}	0 kgm^2	x_G	0 m
y_G	0 m	z_G	30.2 m
h	20 km	u_0	10 m/s

The simulation program is applied to analyze the maneuverability of the platform. The initial state of the platform is the steady horizontal flight condition with a longitudinal velocity of $u_0=10$ m/s , and the other motion parameters all are selected to be zero. Simulation results are shown in Fig. 3-5.

Fig. 3 represents the responses of the platform to a thrust increment of 2kN. The longitudinal velocity is the main response to the thrust control input, and it increases in the proportion of 0.03 m/s^2 approximately, from 10m/s to 12m/s within 60s. The response of vertical velocity, pitch angular velocity and pith angle to the thrust control input is little, which demonstrates that the variety of thrust can not affect these motion parameters almost.

Fig. 4 represents the responses of the platform to 0.1rad step input of elevator. The longitudinal velocity occurs small oscillation, and keeps a stable value of 10m/s after 1 min; the vertical velocity increases negatively and keeps a stable value of -0.5m/s after 40s; pitch angular velocity attenuates to zero with 20s; pitch angel increases negatively and keeps a stable value of -0.08rad after 40s. Down-deflection of elevator generates reverse pitching torque, which induces vertical velocity and pitch angle to increase negatively. Pitch angular velocity is a rapid variable and reflects the short period mode, while pitch angle and vertical velocity are slow variables and reflect the long period mode.

Fig. 5 represents the responses of the platform to 0.1rad step input of rudder. The lateral velocity increase to 0.6m/s with 30s, and the slope of the transition curve descend slowly, which demonstrates that sideslip damp is existing during the response of lateral velocity; the roll angle and roll angular velocity of the platform both occur oscillations, and the oscillation is convergent, which demonstrates the oscillatory roll mode of attitude motion; the yaw angular velocity occurs oscillation and keeps a stable value of -0.008rad/s after 20s, which demonstrates the coupling of roll motion and yaw motion.

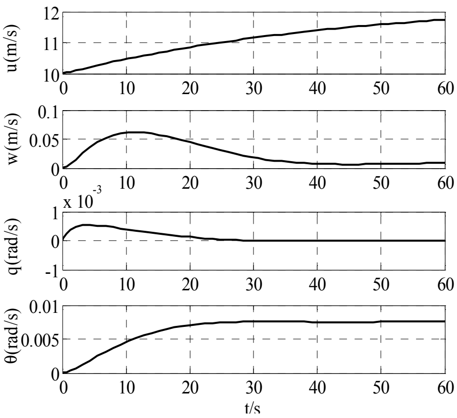

Figure 3. Response to 2kN input of thrust

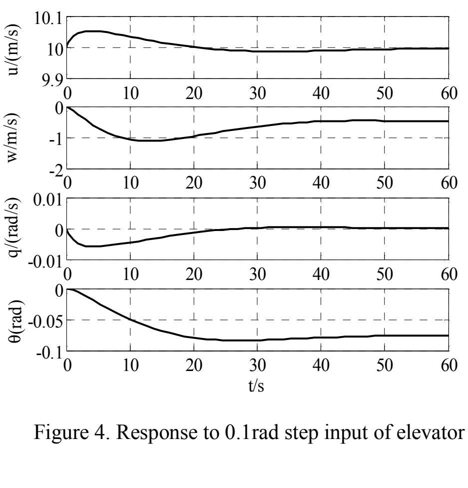

Figure 4. Response to 0.1rad step input of elevator

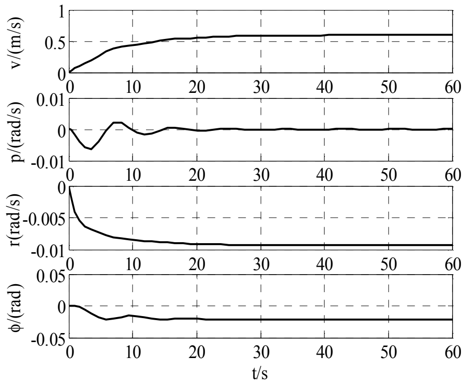

Figure 5. Response to 0.1rad step input of rudder

V. CONCLUSIONS

A concept design and a 6 DOF dynamics model of the near-space earth observation platform is presented in the study. A simulation program based on the model is developed to study the transient responses and maneuverability of the platform. The maneuverability of the platform is shown as follows: thrust increment input induces longitudinal velocity increases gradually, while the response of vertical velocity, pitch angular velocity and pith angle to the thrust control input is little; down-deflection of elevator generates reverse pitching torque, which induces vertical velocity and pitch angle to increase negatively; right-deflection of rudder generates yawing torque, and lateral velocity is affected by the sideslip damp. The response of the platform to the elevator and rudder is small and slow, which demonstrates that efficiency of aerodynamic control surface is not available. Therefore, the vectored-thrust propellers are necessary to be equipped to provide effective control.

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