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SKY SAILING OF TETHERED AEROSTATS FOR EFFICIENT AERIAL MONITORING

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Abstract *This contribution introduces the concept of sky sailing, which combines the advantages of airships and standard fixed-wing aircraft, albeit in a vertical plane alignment. The proposed vehicle is equipped with rigid aerodynamic sails and auxiliary engines, enabling navigation and control with minimal power consumption along the desired trajectory. The proper orientation of the airship relative to the wind direction is achieved through the adjustment of the sails' angle of attack and the use of auxiliary lateral engines. Consequently, the system enables efficient maneuvering, particularly in windy conditions, while requiring low energy input. In the current stage of our research, we focus on 2D sky sailing in a horizontal plane. This study formulates mathematical model which employs a combined approach of analytical methods and numerical simulations based on finite volume method. Then, the corresponding control problem aimed at following the desired fly path with the lowest possible energetic cost. The motivation behind this work stems from the potential applications of aerial monitoring, such as crop or forest surveillance.*

Keywords: Airship, flight control, optimization, aerospace

1. INTRODUCTION

Balloons, aerostats and airships are widely applied as High Altitude Pseudo Satellites (HAPS) for environment and aerial monitoring as well as surveillance missions [1-2]. The rapid development of materials and electronic devices has influenced the advances in the field of airborne vehicles [3-5]. Many research works are devoted to solving problem of predicting the movement of airships in both the vertical and the horizontal direction [6-7], as well as to analysis of the changes in volume and corresponding buoyancy force resulting from heating of the envelope by the sun and heat exchange with the environment [8-9]. However, the problem of control of such vehicles remains difficult due to variable atmospheric conditions. Proposed by [10] solution to control the horizontal balloon drift across the wind involved the development of a balloon guidance system (BGS) and its in-flight tests. The idea of this system is based on application of an aerodynamic wing suspended beneath the balloon (1km or more) by means of a tether. The drag forces are controlled using winch system for lowering and raising the wing leading to stabilizing the balloon position. In another application, the software tools were developed focusing on station-keeping of high altitude balloon, exploiting the natural wind conditions [11]. By using altitude control system based on venting and pumping processes the efficient stabilization of the platform within designated district was achieved.

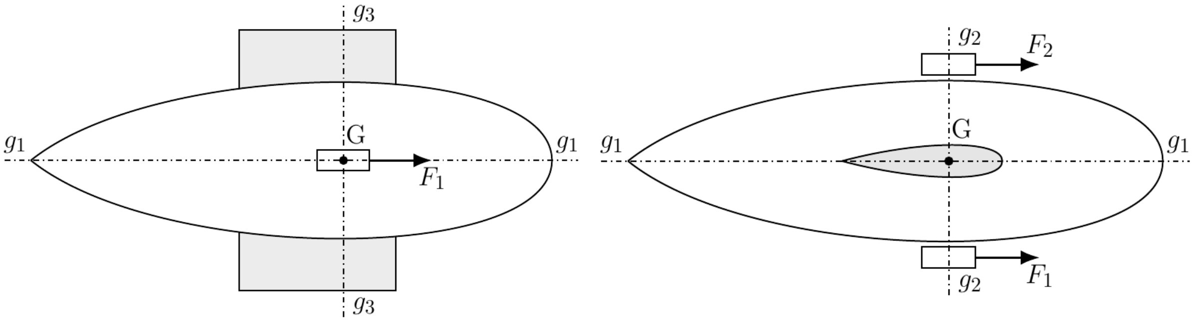
In the previous paper [12], the authors proposed construction of the aerostat based on deployable ultra-light rod-cable tensegrity structure integrated with envelope and equipped with elements of controllable lengths. Such construction enables convenient transport of the aerostat with the use of a balloon or an aircraft to the operational altitude and its automatic deployment at certain location at the atmosphere. On the other hand, the application of adaptable elements enables change of the aerostat volume and shape during the flight. In turn, the procedures for buoyancy control of a tensegrity-based aerostat were presented in [13]. The ultra-light rod-cable tensegrity structure instrumented with electronic devices was proved to enable precise control volume of the aerostat, the corresponding buoyancy force and resulting aerostat horizontal motion. The presented numerical examples have shown the possibility of accomplishing various flight missions by using volume and shape control.

The current contribution introduces the concept of *sky sailing*, which allows to combine the advantages of lighter-than-air vehicles and standard fixed-wing-aircrafts. According to the proposed concept, the aerostat is equipped with a rigid sail of aerodynamic profile and auxiliary engines of small power consumption. The engines provide desired orientation of the aerostat with respect to the wind direction, while the sail causes generation of additional aerodynamic forces influencing motion of the aerostat. As a result, the system enables efficient tacking in the wind and low-energetic motion of the aerostat. In the current stage of the research, for the sake of simplicity we consider a basic problem of sky sailing in the horizontal plane, where the vertical components of aerodynamic forces and buoyancy changes are neglected.

The remainder of the paper is organized as follows. The second section presents a mathematical model describing the *sky sailing* concept, which is based on equations of motion of the aerostat in horizontal plane and numerically determined changes of aerodynamic forces in terms of the system configuration and the wind velocity. The third section shows results of the conducted computational fluid dynamics (CFD) analyses including air velocity fields and aerodynamic forces resulting from the wind flow around the aerostat for various angles of attack. In the fourth section we formulate a control problem aimed at following the desired flight path with minimal energetic cost of the engines operation and analyse its basic features. Finally, in the fifth section general conclusions about modelling, control and advantages of the *sky sailing* concept are presented.

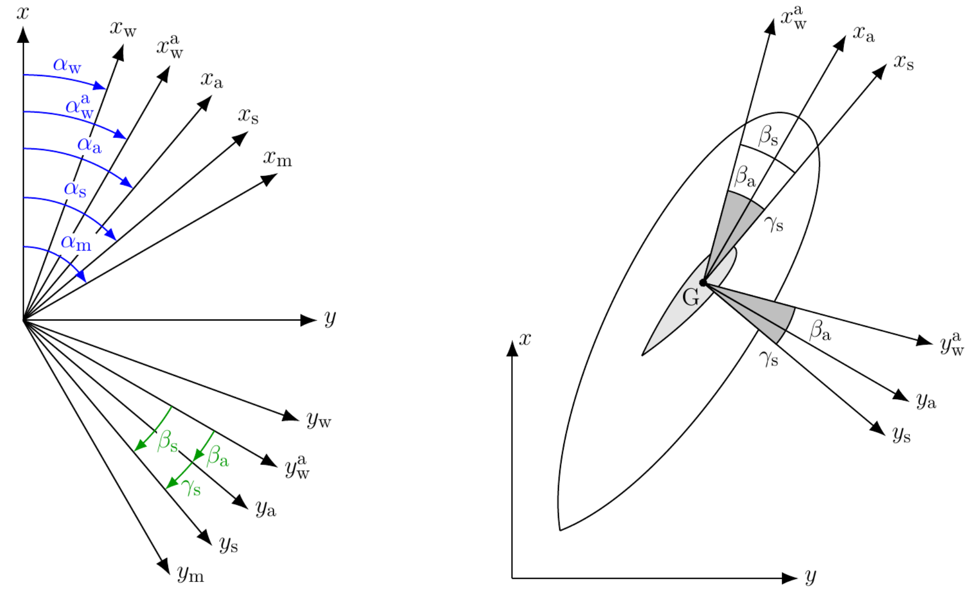
2. MATHEMATICAL MODEL OF THE SKY SAILING

The proposed concept of sky sailing effectively combines the advantages of airships and standard fixed-wing aircraft. The advantages of the airship are achieved by using lighter-than-air gas (helium or hydrogen) in order to obtain buoyancy force and stable position at the assumed altitude under certain atmospheric conditions. In addition, the proposed airship is equipped with rigid sails of aerodynamic profile aligned in the vertical plane (Fig. 1a, side view) and auxiliary lateral engines (Fig. 2b, horizontal view). The combination of the vertical sails and auxiliary lateral engines enables effective usage of aerodynamic forces and obtaining the effect of drifting in the wind in the direction deviated from the wind direction. The proper orientation of the airship relative to the wind direction and its energy saving motion in space are achieved via proper adjustment of the engines' power and sails' angle of attack. Consequently, the system enables efficient maneuvering and navigation, particularly in windy conditions, while requiring low energy input.



(a) Side view (b) Top view

Figure 1. Airship model.



(a) Global and local coordinate systems (b) Local coordinate system for aerostat and sail orientation

Figure 2. Coordinate systems using in mathematical model of the aerostat

The fundamental mathematical model of the *sky sailing* concept refers to the motion of the aerostat in the horizontal plane. In such a model we consider exclusively aerodynamic forces acting in horizontal plane, while the variations of buoyancy and perturbation of vertical forces (e.g. due to temperature changes) are neglected. The starting point for development of the mathematical model is proper definition of the auxiliary coordinate systems and their orientation angles with respect to global coordinate system. In particular, Fig. 2a presents four angles denoted by α which are referred to global coordinate system, namely: α_w – the wind direction, α_a – the aerostat main axis direction g_1 (see Fig. 1a), α_s – the sail axis direction, and α_m – the aerostat motion direction. In addition, α_w^a is the wind direction relative to the direction of the aerostat motion, which results from both the direction α_w and velocity of the wind v_w as well as the direction α_m and velocity of the aerostat motion v_m in a global coordinate system:

$$\alpha_w^a = f(\alpha_w, v_w, \alpha_m, v_m). \tag{1}$$

On the other hand, the angles denoted by β are referred to relative wind direction, namely: β_a – the direction of the aerostat with respect to relative wind direction and β_s – the direction of sail with respect to relative wind direction. Both the β_a and β_s denote the angles of attack (of the aerostat and sail, respectively) and they can be used for simple and intuitive parameterization of the results obtained from CFD analyses. Moreover, both these angles can be expressed in terms of angles in global coordinate system:

$$\beta_a = \alpha_a - \alpha_w^a, \;\; \beta_s = \alpha_s - \alpha_w^a. \tag{2}$$

Finally, γ_s denotes angle between the sail and the aerostat:

$$\gamma_s = \alpha_s - \alpha_a = \beta_s - \beta_a. \tag{3}$$

Let us note that according to the above discussion, we have distinguished eight angles and four relations between them, which reveals that four angles remain independent. The set of independent angles can be conveniently selected as: $\alpha_w, \alpha_a, \gamma_s, \alpha_m$, where: α_w – is a given time-dependent quantity, α_a – is one of the main unknowns of the system, γ_s – is one of the control variables, while γ_m – can be expressed in terms of basic unknown components of aerostat motion x and y.

The next step of model development is computation of aerodynamic forces and moments acting on the aerostat with respect to the angles of attack β_a and β_s as well as the wind velocity relative to the aerostat v_w^a. These forces and moments are determined using the CFD model of the flow around aerostat described in the next section. The forces acting in the direction parallel and perpendicular to the wind direction (P_1 and P_2) as well as torque acting on the aerostat M_P can be expressed in general forms:

$$P(\beta_a, \beta_s, v_w^a) = P(\alpha_a, \alpha_s, \alpha_w^a, v_w^a) = P(\alpha_a, \gamma_s, \alpha_w, v_w, \alpha_m, v_m) = P(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}), \tag{4}$$

where: $P = \{P_1, P_2, M_P\}$. Further, forces refereed to global coordinate system (P_x and P_y) can be calculated using standard transformation:

$$\begin{bmatrix} P_x \\ P_y \end{bmatrix} = \mathrm{T}(\alpha_w^a) \begin{bmatrix} P_1(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}) \\ P_2(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}) \end{bmatrix} = \begin{bmatrix} P_x(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}) \\ P_y(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}) \end{bmatrix},$$

while the torque M_P does not require transformation to global coordinate system and thus $\mathrm{T}(\alpha_w^a)$ is the transformation matrix with dimensions 2 by 2. Let us note that determined forces depend on angle of aerostat rotation α_a, angle of the sail γ_s (one of system control variables), known direction and velocity of the wind α_w and v_w as well as unknown components of aerostat velocity $\dot{x}, \dot{y}$. Similarly, forces generated by the auxiliary lateral engines in local coordinate system of the aerostat $\{F_1, F_2\}$ can be transformed to global coordinate system and expressed as follow:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \mathrm{T}(\alpha_a) \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} F_x(F_1, F_2, \alpha_a) \\ F_y(F_2, F_2, \alpha_a) \end{bmatrix}. \tag{5}$$

Moreover, the torque corresponding to the operation of the engines M_F can be calculated in a standard manner.

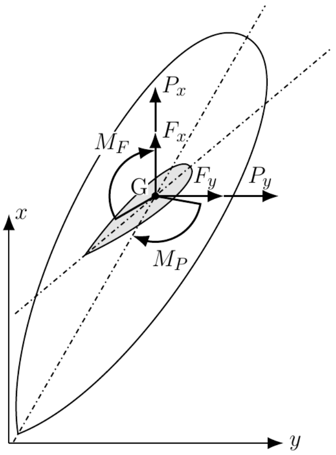


Figure 3. Force systems acting on the airship (top view).

The above dependencies allow to define equations of motion governing the process of *sky sailing* in the horizontal plane:

$$\begin{aligned} m\ddot{x} &= P_x(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}) + F_x(F_1, F_2, \alpha_a) \\ m\ddot{y} &= P_y(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}) + F_y(F_1, F_2, \alpha_a) \\ I\ddot{\alpha}_a &= \ M_P(\alpha_a, \gamma_s, \alpha_w, v_w, \dot{x}, \dot{y}) + M_F(F_1, F_2, \alpha_a) \end{aligned} \tag{6}$$

where m is the total mass of the airship, I is the moment of inertia of the airship, P_x and P_y are components of aerodynamic forces acting on the airship in the *x* and *y* direction, respectively, F_x and F_y are forces generated by the propulsion system in the *x*- and *y*-direction, respectively, while M_F and M_P are torques generated by aerodynamic forces and propulsion system, respectively. The presented form of the governing equations reveals the dependencies of generated forces and torques on the main unknowns of the problem x, y, α_a, known parameters of the wind α_w, v_w as well as control variables γ_s, F_1, F_2.

3. NUMERICAL ANALYSES OF THE FLOW AROUND AEROSTAT

Numerical studies related to the determination of the values of forces and torques acting on the aerostat model and used in equations of aerostat motion (Eq. 6) were carried out using Ansys Fluent software. The obtained results allowed to create the database established for given, discretized values of aerostat hull and sails angles of attack wind velocity as well as wind velocities. For the purpose of solving the Eq. 6 the intermediate values of forces and torques were interpolated.

The full 3D numerical model of the airship consists of a hull and two sails in the form of aerofoils mounted rotatably in a controlled way with respect to a vertical axis passing through the centre of gravity G of the entire structure. The position of the centre of gravity G was determined based on the design of the structure equipped with the basic systems necessary to perform the assumed mission. The profile model of the aerostat section axis has a length of 12 m in the longitudinal and a diameter of maximum value of 3 m. The value of the aerostat's lateral area is equal to 91.56 m², while the projected area of the aerostat's surface is 7.08 m^2 in the longitudinal direction and 28.22 m^2 in the transverse direction.

The aerostat is equipped with two sails mounted vertically under and above the hull with possible rotation about the vertical axis g_3 (see Fig 1a). A single sail has a length of about 2.97 m, a maximum width of 0.551 m and a height of 1.995 m. The value of the lateral area of the entire sail is 12.31 m^2, and the projected area of the aerostat surface in the longitudinal direction is 0.895 m^2 and in the transverse direction is 5.98 m^2. It can be seen that the values of the projected areas of the sail are relatively large compared to the projected areas in the corresponding directions.

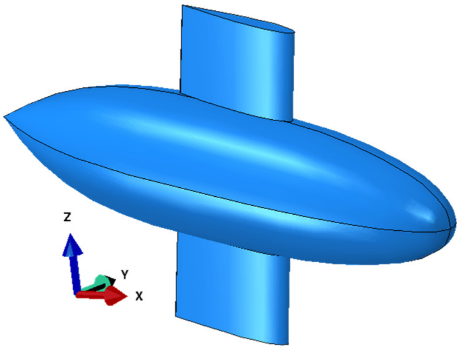


Figure 4. Designed airship geometry used for finite volume method analysis.

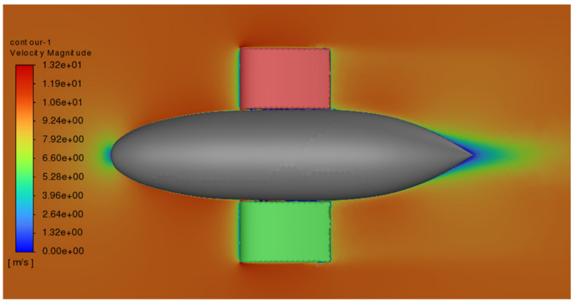


Figure 5. Airflow velocity distribution in the XZ plane: $\beta_s = 0,\ \beta_a = 0,\ v = 10m/s$.

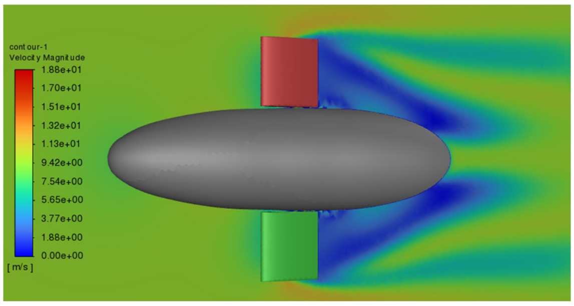


Figure 6. Airflow velocity distribution in the XZ plane: $\beta_s = 15, \beta_a = 15,\ v = 10m/s$.

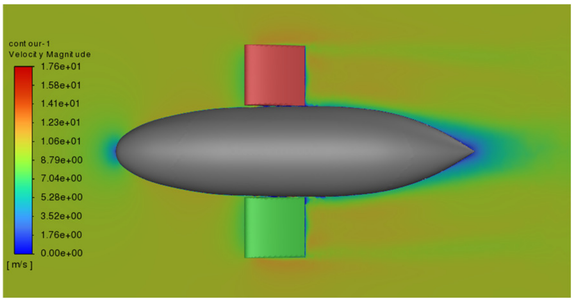


Figure 7. Airflow velocity distribution in the XZ plane: $\beta_s = 15,\ \beta_a = 0, v = 10m/s$.

During the analyses, it was assumed that the aerostat is surrounded by air with a density resulting from a given altitude, which was selected based on the NASA atmosphere model[i]. It was assumed that in each direction the space surrounding the aerostat have a size of 40 by 60 m, whose length ratio is between 3.5 and 5 values of the aerostat's length. The conducted simulations have shown that this is a sufficient value for analysis. The numerical model of the aerostat and the surrounding air consist of 3.6 million nodes, 4.4 million surface elements refined in the areas of geometry changes. The mesh in the vicinity of the aerostat and sails was also refined. Further away from the model at the edges of the fluid model, a larger elements dimensions were used. Based on the aforementioned nodes and surface elements, a fluid mesh of about 660 thousand polyhedral cell volume elements was created. In order to reflect the basic fluid behaviour in the boundary layer, a boundary layer consisting of 5 volume elements was built.

The numerical model of the aerostat including sails was parameterized by using the following assumptions concerning parameters variations:

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[i] The model is available at NASA's web page (accessed 2023 May 31): https://www.grc.nasa.gov/www/K-12/airplane/atmosmet.html.

- The parameter describing the angle of deflection of the aerostat in the horizontal plane – during the analyses, the variation in the range of –30 to +30 degrees from the direction of airflow was allowed;
- The parameter describing the angle of deflection of the sails relative to the fuselage – during the analyses, the angle was allowed to vary in the range of –15 to +15 degreed relative to the hull;
- The air velocity was varied in the range of 2.5–10 m/s. The range of such speeds was due to the assumption of the limitation of wind speed in real conditions during the planned experimental tests.

During the numerical tests, the air flow was assumed to occur in the horizonal XY plane in the X-axis direction. The vertical direction was described by the Z-axis. The simulations were carried out for various combinations of the above-mentioned parameters, which allowed to determine the values of forces acting in each direction and the values of moments with respect to each mentioned axis. The values of moments were determined with respect to axes passing through the centre of gravity G located in the axis of the aerostat at a distance of 5.75 m from its tip.

Figures 5-7 show the distribution of velocity in the XZ plane around the aerostat for different hull and sail deflection angles. It can be seen that both changing the angle of the hull relative to the wind and the sail causes significant changes in the streamlining of the aerostat with the sails by the air.

4. FORMULATION OF THE CONTROL PROBLEM FOR SKY SAILING

The control problem corresponding to the sky sailing concept involves following the assumed trajectory of aerostat horizontal motion with minimal energetic cost. The most general form of the objective function includes the integral term denoting global error of the trajectory tracking and integral term denoting work done by auxiliary engines. The control is conducted with respect to actual angle of the sail and forces generated by the engines. The constraints of the problem are equations of motion of the system. The complete mathematical formulation of such a control problem takes the form:

$$\text{Minimize: } \int_0^T [s(x,y) - \bar{s}(x,y)]^2\, dt + q \int_0^T \left[F_x \dot{x} + F_y \dot{y}\right] dt$$

$$\text{with respect to: } \gamma_S(t), F_1(t), F_2(t)$$

$$\text{subject to: } m\ddot{x} = P_x + F_x, \quad m\ddot{y} = P_y + F_y, \quad I\ddot{\alpha}_a = M_P + M_F$$

where $\bar{s}(x,y)$ denotes the assumed trajectory of motion in the horizontal plane, while q is the weighting coefficient of the control cost term. Let us note that one of the proposed control variables $\gamma_S(t)$ corresponds to the semi-active control of the proposed system, while two remaining control variables $F_1(t)$ and $F_2(t)$ correspond to the active control. Therefore, the presented formulation can be considered as a joint problem of semi-active and active control. However, depending on the value of the weighting coefficient of the control cost term q, two opposite cases can be distinguished. In the first case, by setting relatively large value of the weighting coefficient, the active control terms are eliminated and the formulation becomes a semi-active control problem with respect to angle of the sail $\gamma_S(t)$. In the second case, when the weighting coefficient is set to zero the control problem is aimed at optimal following of the assumed trajectory regardless of the control cost.

The above formulated control problem can be solved using various approaches, semianalytical or numerical methods. One of the possibilities is application of the so called *inverse dynamics method* known from the problems of adaptive impact absorption. The possibilities of applying such method to both above mentioned versions of the control problem will be the subject of the further research.

5. CONCLUSIONS

The article presents the concept of an airship propelled by two engines and equipped with vertical sails with adjustable angle of attack. The objective of the work is to present an effective approach for controlling the airship motion by using aerodynamic loads generated by the sails while minimizing the engines' usage. In order to solve this problem, a 2D mathematical model with three degrees of freedom (airship rotation angle and two displacements) is developed, where the control is achieved by changing sails' angle of attack and engines' thrusts. The mathematical model is supported by a three-dimensional finite volume model developed in the Ansys Fluent, which is used to create a reference database containing aerodynamic forces acting on the airship for selected discrete values of wind directions and sails attack angle. Eventually, the problem of airship sailing along a pre-defined mission path at a fixed altitude is formulated, and potential methods of its solution are proposed. Such defined problem, particularly the numerical analysis of controlled airship movement, will be the subject of further work of the authors.

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