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PD-computed torque control for an autonomous airship

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ABSTRACT

For the trajectory following problem of an airship, the standard computed torque control law is shown to be robust with respect to unknown dynamics by judiciously choosing the feedback gains and the estimates of the nonlinear dynamics. In the first part of this paper, kinematics and dynamics modeling of the airships is presented. Euler angles and parameters are used in the formulation of this model and the technique of Computed Torque control is introduced. In the second part of the paper, we develop a methodology of control that allows the airship to accomplish a prospecting mission of an environment, as the follow-up of a trajectory by the simulation who results show that Computed Torque control method is suitable for airships.

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1. INTRODUCTION

Robust control of the autonomous airship has been the subject of considerable research over the last decade. The advantage of robust control over other control schemes is that robust control can be used in the presence of nonlinear dynamics. In the tracking control of the airship, the computed torque control law is commonly used. The computed torque control law has been shown to make the error system asymptotically stable, if the dynamics of the airship are exactly known. The Autonomous airship as typical lighter than air vehicle represents a unique and promising platform or various applications (civil and military). Such as telecommunications, broadcasting, the environmental protection (measurement of the air pollution, monitoring of the forests), scientific exploration [1]. There is a lot of key technologies to be realized for autonomous airship. One of the most important techniques is flight control system. Some contributions on dynamic modeling and control system have been reported in recent years [1]. The airships have a very low cost to maintain themselves in flight and have the possibility to fly in low altitude and with low speed. Airship is a member of family of under-actuated systems as it has fewer inputs than degrees of freedom and the principle of Archimedes applies in the air as well as under water.

In this paper, the complete model (kinematic and dynamic) of the autonomous airship is presented, based on the Newton-Euler approach with analysis of gravity, buoyancy, aerodynamics, damping and thrust. This model is developing by [2]. The main objective of this article is the synthesis of stabilizing control laws in terms of translation and orientation for the airship. It's a vehicle has the difficulty of the control because its complex, non-linear dynamics, multivariable, of coupled nature, particularly in its operation and sensitivity to the external disturbance. The backstepping controller is proposed to solve this problem (control). The control strategy is based on the decomposition of the original system into two subsystems: the first concerns the position control while the second is to control orientation and the velocity.

There are many published works on the dynamic model and the control of lighter than air vehicles. In [3-5] motion is referenced to a system of orthogonal body axes located in the airship. This model was formulated originally for a buoyant underwater vehicle [3]. It was modified later to take into account the specificity of the airship [4, 5]. This model was modified by [6] and the modification has the particularity that origin of the airship fixed frame is located in the centre of gravity. Recall that the centre of buoyancy is the centre of the airship volume. But in these papers, new dynamic model developed by [2] we used and we propose to control of this model.

Many works are published in the control of the lighter than air vehicles, for example: in [7] the authors are proposed the linear control theory applied for the linearization. In [1] a fault-tolerant Backstepping control law is proposed. In [8] the authors proposed nonlinear adaptive controller design to stabilize the error system by Lyapunov direct method and Matrosov theorem. While in the cited works, they have used the decoupled linear models comprised of the longitudinal and lateral models. In [9] the authors have addressed the problem of designing tracking feedback control. In [10] they designed an adaptive feedback linearization control. In [11] an improved sliding mode control is presented. In [12] the dynamics in the vertical plane are analyzed and controlled, using maximal feedback linearization. In [13] a fuzzy adaptive backstepping control is presented, and the trajectory control method for under actuated stratospheric airship is proposed in [14] based on TLC theory. In [15] a backstepping controller was designed for attitude and velocity. In [16] a robust backstepping controller considering disturbance was proposed. In [17] a robust feedback controller is presented. In this paper, the computed torque controller and motion planning are combined to stabilize the Airship by using the point to point steering stabilization. Modeling is briefly described in Section 2. Section 3, describes computed torque controllers. In Section 4, simulation results are presented followed by robustness consideration in Section 5. Finally, some conclusions and future work are given in the last sectiona.

2. MODELING OF THE AIRSHIP

The airship Figure 1 studied here has a traditional ellipsoidal envelope. It aims to fly in the stratosphere. Buoyancy is provided by helium contained in the envelope. The avionics system, power system and payloads are equipped in a gondola fixed below the envelope. The aerodynamic control surfaces like rudders and elevators attach to the empennage surfaces. In this research, the up and down rudders move together, while the left and right elevators are differential and move separately. Therefore, the deflections of the rudders control the yaw movement whereas the elevators influence the pitch and rotation. The propellers are fixed on both sides of the gondola and provide main propulsive force for flight.

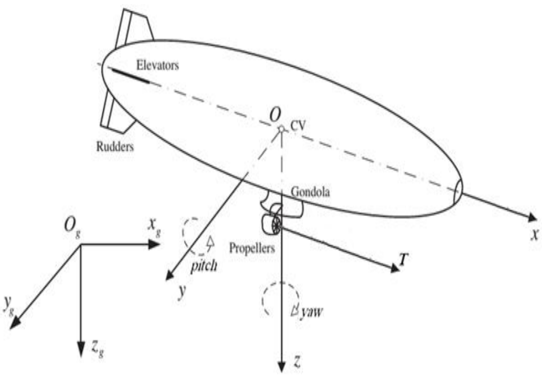

Figure 1. Structure of the airship

The dynamic modeling of lighter than air (airship) is deduced from Newton's laws of classical mechanics. We are analyzing the motion of an airship with six degrees of freedom, whereas. We are considering the velocity of the wind is null. We described two references frames (inertial and body-fixed), then, the three-dimensional translational kinematic equations of an aerial vehicle taking into account the wind effect can be expressed as following (1):

$$\begin{cases} dx = V\cos(\psi)\cos(\gamma) \\ dy = V\cos(\gamma)\sin(\psi) \\ dy = V\sin(\gamma) \end{cases} \quad (1)$$

Where X and Y define the horizontal position of the vehicle and Z denotes its altitude. The translation equations are followed as (2):

$$\begin{cases} \dot{\gamma} = \dfrac{\begin{bmatrix} (L + T\sin(\alpha))\cos\cos(\sigma) \\ -(b - mg)\cos(\gamma) \end{bmatrix}}{(m + m_{33})V} \\ \dot{\Psi} = \dfrac{(L + T\sin(\alpha))\sin(\sigma)}{(m + m_{22})V\cos(\gamma)} \\ \dot{V} = \dfrac{1}{m + m_{11}} \begin{bmatrix} T\cos(\alpha) - D \\ +(b - mg)\sin(\gamma) \end{bmatrix} \end{cases} \quad (2)$$

These equations are a result of aerodynamics, gravity, buoyancy, lift, drag and thrust forces moments, and are controlled by the thrust T ,the angle of attack α and the bank angle σ [2]. Aero dynamical Force: This force includes the drag force D, opposite to V, and the lift force L, orthogonal to V. These forces are expressed by the following (3):

$$\begin{cases} L = \dfrac{1}{2} C_L(M, \alpha) A_r \rho V^2 \\ D = \dfrac{1}{2} C_D(M, \alpha) A_r \rho V^2 \\ b = \rho * Vol * g \end{cases} \quad (3)$$

The lift coefficient is a linear function of the angle of attack whilst the drag coefficient is a quadratic function of $C_L(M, \alpha)$ (4) [18]:

$$\begin{cases} C_L(M, \alpha) = C_{L0}(M) + K_{L\alpha}(M)\alpha \\ C_D(M, \alpha) = C_{D0} + KC_L^2 \end{cases} \quad (4)$$

These equations have an important place in aerospace vehicle study, because they can be formulated from trimmed aerodynamic data and simple autopilot designs. Nevertheless, they give a realistic picture of the translational and rotational dynamics unless large angles and cross-coupling effects dominate the simulations. Trajectory studies, navigation, and guidance evaluations can be successfully executed with simulations of these equations. The limitations on thrust and velocity will be used in the path planning [18-20].

3. NONLINEAR COMPUTED TORQUE CONTROL

3.1. For the dynamic model

The velocity, the pitch and the yaw can be controlled by a feed forward controller Figure 2. From the model (2) one can see that through the velocity V depends on T and the other hand σ and α are controlled through the angles Ψ, γ respectively.

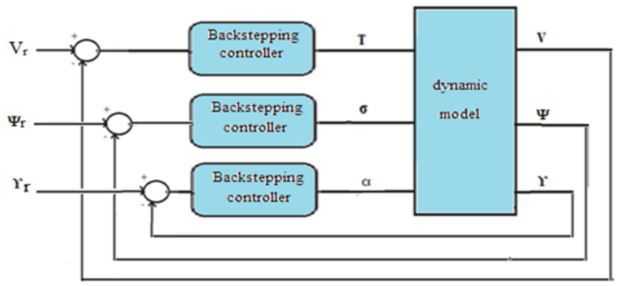

Figure 2. Computed torque controller for dynamic model

The computed torque algorithm to develop the control allowing the system to follow the desired trajectory, we consider the tracking error (6):

$$e_{v1} = V - V_r \tag{6}$$

V_r : is the desired velocity. Its derivative is computed as (7):

$$\dot{e}_{v1} = \dot{V} - \dot{V}_r \tag{7}$$

The nonlinear feedback control law that guarantees tracking of desired trajectory. Selecting Proportional plus derivative (PD) feedback for U (t) results in the PD-computed torque controller [3], the final control is (8):

$$\dot{T} = \frac{\begin{bmatrix} T\dot{\alpha}\sin(\alpha) + \dot{D} \\ -\dot{\gamma}(b - mg)\cos\cos(\gamma) \\ +\left(\ddot{V}_r - K_{v1}e_v - K_{v2}\dot{e}_v\right)(m + m_{11}) \end{bmatrix}}{\cos\cos\alpha} \tag{8}$$

and the resulting linear error dynamics are (9):

$$\left(\ddot{V}_r - K_{v1}e_v - K_{v2}\dot{e}_v\right) = 0 \tag{9}$$

According to linear system theory, convergence of the tracking error to zero is guaranteed. The yaw and pitch attitudes can be stabilized to a desired value with the following tracking feedback control (10-11).

$$\dot{\alpha} = \frac{\begin{bmatrix} \left((L + T\sin\alpha)\cos\sigma + (B - mg)\cos\gamma\right)\dot{V} \\ +V\dot{\sigma}(L + T\sin\alpha)\sin\sigma \\ -(\dot{L} + \dot{T}\sin\alpha)V\cos\sigma \\ -V\dot{\gamma}(B - mg)\sin\gamma \\ +\left(\ddot{\gamma}_r - K_{\gamma1}e_\gamma - K_{\gamma2}\dot{e}_\gamma\right)(m + m_{33})V^2 \end{bmatrix}}{T\,V\cos\alpha\cos\sigma} \tag{10}$$

$$\dot{\sigma} = \frac{\begin{bmatrix} \begin{pmatrix} \dot{V}\cos\sigma \\ -V\dot{\gamma}\sin\gamma \end{pmatrix}(L + T\sin\alpha)\sin\sigma \\ -\begin{pmatrix} (\dot{L} + \dot{T}\sin\alpha + T\dot{\alpha}\cos\alpha) \\ V\sin\sigma\cos\gamma \end{pmatrix} \\ +\begin{pmatrix} (m + m_{22}) \\ V^2\cos^2\Psi \end{pmatrix}\left(\ddot{\Psi}_r - k_{\Psi1}e_\Psi - k_{\Psi2}\dot{e}_\Psi\right) \end{bmatrix}}{(L + T\sin\alpha)V\cos\sigma\cos\gamma} \tag{11}$$

where $K_{v1}, K_{v2}, K_{\gamma1}, K_{\gamma2}, K_{\Psi1}$ and $K_{\Psi2}$ are the coefficients ensuring stability and are positive constants.

3.2. For the kinematic model

In Figure 3 is the motion through the axes X, Y and Z can be controlled by a feed forward controller.

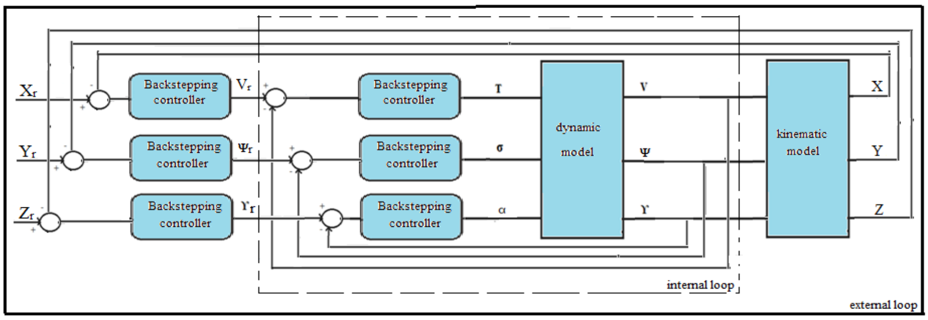

Figure 3. Computed torque controller for kinematic model

From the model (1) one can see that the motion through the axes Z depends on γ, on the other hand V and Ψ control the motion through the axes X, Y respectively. This leads to a Backstepping controller for which X, Y, Z are given by (12-14):

$$\dot{V} = \frac{\begin{bmatrix} \ddot{X}_r - k_{X1}e_X - k_{X2}\dot{e}_X \\ +V\left(\dot{\Psi}\sin\Psi\cos\gamma + \dot{\gamma}\sin\gamma\cos\Psi\right) \end{bmatrix}}{\cos\Psi\cos\gamma} \tag{12}$$

$$\dot{\Psi} = \frac{\begin{bmatrix} \ddot{Y}_r - k_{Y1}e_Y - k_{Y2}\dot{e}_Y \\ -\left(\dot{V}\cos\gamma - V\dot{\gamma}\sin\gamma\right)\sin\Psi \end{bmatrix}}{V\cos\Psi\cos\gamma} \tag{13}$$

$$\dot{\gamma} = \frac{\left[\ddot{Z}_r - k_{Z1}e_Z - k_{Z2}\dot{e}_Z - \dot{V}\sin\gamma\right]}{V\cos\gamma} \tag{14}$$

where $K_{X1}, K_{X2}, K_{Y1}, K_{Y2}, K_{Z1}$ and K_{Z2} are the coefficients ensuring stability and positive constants.

4. SIMULATION

To evaluate the designed control system, repetitive simulation tests were performed via numerical simulation. The control system was simulated using the variable step Runge–Kutta integrator in MATLAB. The airship is tested in simulation in order to validate motion planning algorithm considering the proposed Computed Torque controller. The general specifications of the vehicle are as follow:

$m = 18.375\ (Kg);\ Vol = 15\ (m^3);\ \rho = 1.225;$

$m_{11} = 1.247 * \rho(Kg);\ m_{33} = 16.671 * \rho(Kg);$

$m_{22} = 17.219 * \rho(Kg);\ g = 9.8\ \left(\frac{m}{s^2}\right);$

$CD_0 = 0.5;\ CL_0 = 0.024;\ CL_1 = 0.937$

$K = 1.4; A_r = 2.84$

The parameters of the computed torque controller are selected as:
For dynamic model:

$K_{V1} = 250, K_{V2} = 130, K_{\Psi 1} = 25, K_{\Psi 2} = 2,$

$K_{\gamma 1} = 16, K_{\gamma 2} = 1.5$

For kinematic model:

$K_{X1} = 16, K_{X2} = 2.3, K_{Y1} = 10.5, K_{Y2} = 5.6,$

$K_{Z1} = 15, K_{Z2} = 6.9$

Figure 4 shows the simulation results of PD-CTC control with accurate parameters and without external disturbances and to confirm the robustness of proposed trajectory tracking control method. As illustrated in the above figures, the convergence to the trajectory is guaranteed after a transient behavior. It can be observed that the airship platform tends to the target point precisely, which demonstrates that the proposed approach succeeds in station keeping control for the airship platform. Figure 6 shows that the position errors and the translation dynamic (velocity and orientations) of the airship platform with accurate parameters and without external disturbances. The position errors are converging to zero, the translation dynamics converge to desired value, and we can see the change of the translations dynamics (angles and velocity) in the moment for this change in the trajectories (20s, 40s, 60s). The above mentioned results demonstrate that the PD-CTC control is accomplished with precision using the designed control system. In conclusion, the simulation results verify that the trajectory tracking control method designed in this paper for airship is efficient.

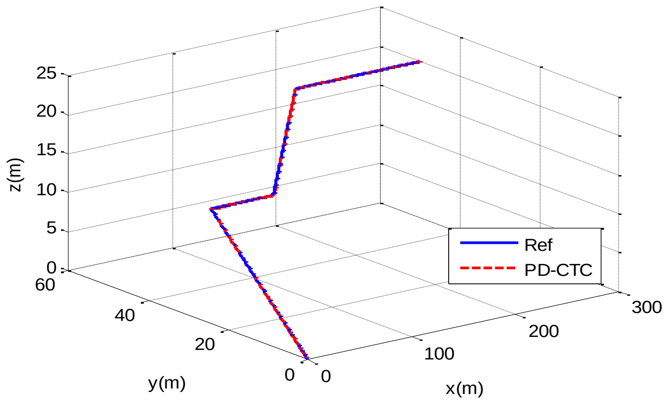

Figure 4. Result of position trajectories without disturbances

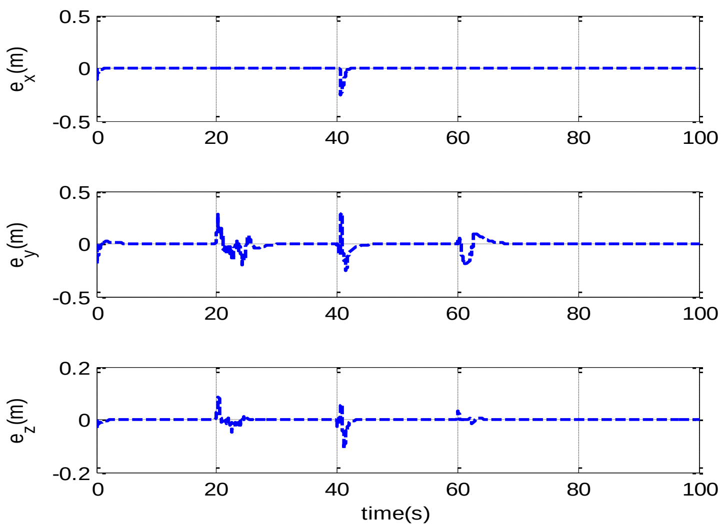

Figure 5. The position errors of the airship without disturbances

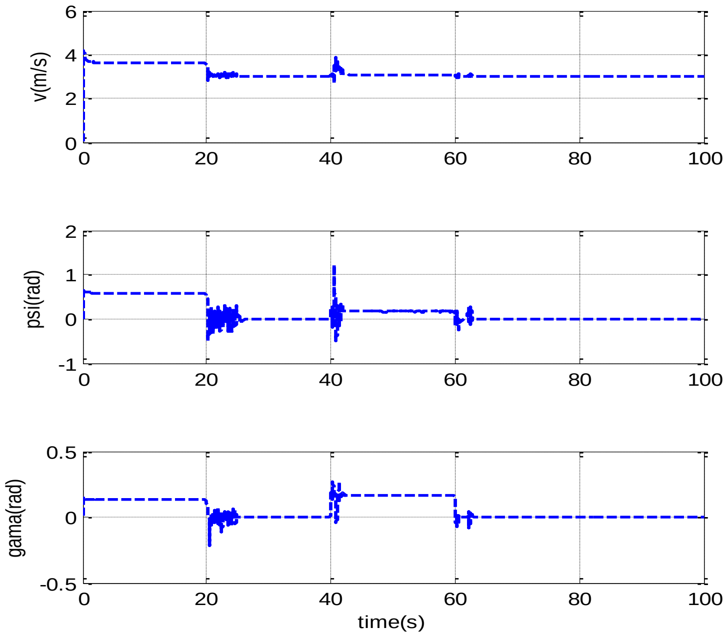

Figure 6. The translation dynamic (velocity and orientations) of the airship without disturbances

5. CONCLUSION

In this paper, we presented synthesis of stabilizing control laws by computed torque approach. Firstly, we start by the development of the dynamic model of the airship taking into account the different physics phenomena, using Newton Euler approach and for complex non-linear movement of blimps we can design its computed torque controllers. As prospects we hope to develop other control techniques in order to improve the performances and to implement them on a real system.

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APPENDIX

$[x, y, z]^T$ Position vector

$[\Psi, \gamma]^T$ Euler angles yaw, pitch

V Velocity of airship

m Masse of the vehicle

T Force developed by propulsion

$[\sigma , \alpha]^T$ Angles of the rudders and elevators

Ar Setting of the reference area

ρ Density of the air

M Mach number

Vol Volume of the vehicle

b = Force of buoyancy

$C_L(M, \alpha), C_D(M, \alpha)$ Parameters of lift and drag

L, D =Lift and drag forces

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Meddahi Youssouf received the Master Degree in Electrical Engineering from University of Sciences and Technology of Oran M-B (USTO), Algeria, in 2009. His research interests include nonlinear control of mechanical systems, and control system analysis and design tools for under-actuated systems with applications to aerospace vehicles in LDEE laboratory.

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