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Airship robust path-tracking: A tutorial on airship modelling and gain-scheduling control design

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ABSTRACT

This paper provides a tutorial view on airship path-tracking under wind disturbances. It addresses the relevant aspects towards this objective, namely the airship modelling, the dynamics analysis over the flight envelope, and the step-by-step design of a gain-scheduling control. The required parts to build a proper airship simulator are given: airship dynamics and actuation, and wind disturbances. A path-tracking gain-scheduling controller is designed and its performance and robustness evaluated in the simulation environment described for a complete airship mission consisting of vertical takeoff and landing, cruise flight and ground-hover, under realistic wind disturbances. Throughout the paper, considerations are done regarding the airship behavior and limitations, as well as what can be accomplished and how.

1. Introduction

Intrinsically more stable than other platforms, airships can fly at very low speeds or even hover, showing a slow degradation in case of a system's failure. Combining the advantages of these platforms and the recent evolution in aerial robotics, and after decades of hibernation, the last 20 years have seen a renewed interest in the use of airships for applications like cargo transportation (Skuza, Park, & Kim, 2014), environmental (Elfes, Bueno, Bergerman, & Ramos, 1998) and urban areas (Kanistras, Martins, & Rutherford, 2014) monitoring, and telecommunications (Yang, Wu, & Zheng, 2012).

Aiming at the autonomous airship goal, aerial platform positioning and path-tracking should be assured by an efficient control and navigation system. The classical linear control design techniques, used for flight control problems for many years, are an easy and intuitive initial guess for design, specially when the objective is a particular flight condition like cruise flight. Following this idea, the first autonomous experimental flight of an airship resulted from the implementation of a PID heading controller, along with an automatic altitude control, for path-tracking through a set of pre-defined points in latitude/longitude (Ramos, Carneiro de Paiva, & Azinheira, 2001). Wimmer, Bildstein, and Well (2002) also demonstrated experimentally the performance of a robust controller, again based on a linearized airship model. Considering a linearized decoupled model of the airship, and again only for aerodynamic flight, solutions for the lateral control include the H_2/H_∞ approach for the design of controllers PD for altitude and heading control and PID for groundspeed control (de Paiva, Bueno, & Gomes, 1999), and state feedback with integral control (Hygounenc & Soueres, 2003).

However, if the automatic control system is to cover the complete aerodynamic range from hover to cruise flight, then the control solution should cope with the nonlinear and under-actuated airship dynamics. The abrupt dynamics transition between the two flight regions, and the different use of actuators necessary within each region, must also be taken into consideration. In this case, nonlinear control approaches are best suited. A global approach based on the backstepping solution (Azinheira, Moutinho, & de Paiva, 2009) guarantees the airship path-tracking over the whole flight envelope, taking into account actuator limitations and being robust to wind disturbances. Besides backstepping (Repoulias & Papadopoulos, 2008), other nonlinear control solutions have been applied to airship autonomous navigation, namely dynamic inversion (also known as feedback linearization) (Moutinho & Azinheira, 2005), sliding mode control (Benjovengo, de Paiva, & Bueno, 2009; Yang et al., 2012) and guidance-based

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Nomenclature

α angle of attack
β sideslip angle
$\boldsymbol{\Gamma} = [\eta, \varepsilon, \delta]^T$ position error vector
δ vertical position error
δ_a aileron deflection
δ_e elevator deflection
δ_r rudder deflection
δ_v main propellers vectoring angle
ε lateral position error
η longitudinal position error
θ pitch angle
$\boldsymbol{\Phi} = [\phi, \theta, \psi]^T$ angular position vector relative to $\mathcal{I}$ frame
ϕ roll angle
ψ yaw angle
$\boldsymbol{\omega} = [p, q, r]^T$ angular velocity in $\mathcal{B}$ frame
$\boldsymbol{\Omega}_6$ see Eq. (6)
$\mathcal{A}$ aerodynamic reference frame
$\mathbf{a}_g = [0, 0, g]^T$ inertial gravity acceleration vector
$\mathcal{B}$ body-fixed (local) reference frame
$\mathbf{c} = [a_x, 0, a_z]^T$ vector from center of volume to center of gravity
D position down
E position east
$\mathbf{E}_g$ see Eq. (6)
$h = -D$ altitude
$\mathbf{F}$ force–torque vector
$\mathcal{I}$ inertial (ground fixed) reference frame
$\mathbf{J}$ inertia matrix of the airship
$\mathbf{J}_B$ inertia matrix of the buoyancy air
$\mathbf{J}_v$ virtual inertia matrix
m airship mass
$\mathbf{K}$ LQR gain matrix
$\overline{\mathbf{M}}_a = \overline{\mathbf{M}}_o + \overline{\mathbf{M}}_v$ generalized apparent mass matrix of the airship
m_B buoyancy mass
$\overline{\mathbf{M}}_B = \mathrm{diag}(m_B \mathbf{I}_3, \mathbf{J}_B)$ generalized inertial mass matrix of the buoyancy air
$\overline{\mathbf{M}}_{Ba} = \overline{\mathbf{M}}_B + \overline{\mathbf{M}}_v$ generalized apparent mass matrix of the buoyancy air
$\overline{\mathbf{M}}_o$ generalized mass matrix of the airship
$\mathbf{M}_v$ virtual mass matrix
$\overline{\mathbf{M}}_v = \mathrm{diag}(\mathbf{M}_v, \mathbf{J}_v)$ generalized virtual mass matrix
$m_w = m - m_B$ weighting mass
N position north
$\mathbf{P} = [\mathbf{p}^T, \boldsymbol{\Phi}^T]^T$ position vector
$\mathbf{p} = [N, E, D]^T$ cartesian position vector in $\mathcal{I}$ frame
p roll rate in $\mathcal{B}$ frame
$\dot{\mathbf{p}} = [\dot{p}_N, \dot{p}_E, \dot{p}_D]^T$ linear velocity and components in $\mathcal{I}$ frame
q pitch rate in $\mathcal{B}$ frame
$\mathbf{Q}$ state weighting matrix
r yaw rate in $\mathcal{B}$ frame
$\mathcal{R}$ reference (trajectory) frame
$\mathbf{R}$ control weighting matrix or transformation matrix (8)
$\mathbf{S}$ rotation matrix (8)
$T_D = T_L - T_R$ engines differential thrust
T_L left engine thrust
T_R right engine thrust
T_x engines longitudinal thrust
T_y tail motor thrust
T_z engines vertical thrust
u forward speed in $\mathcal{B}$ frame
$\mathbf{u} = [\delta_e, T_L, T_R, \delta_v, \delta_a, \delta_r, T_y]^T$ actuation input vector
$\tilde{\mathbf{u}} = \mathbf{u} - \mathbf{u}_e$ perturbation input vector
$\mathbf{u}_e$ equilibrium input vector
$\mathbf{u}_f = [f_u, f_v, f_w, f_p, f_q, f_r]^T$ control force input vector
$\mathbf{V} = [\mathbf{v}^T, \boldsymbol{\omega}^T]^T$ velocity vector
$\mathbf{v} = [u, v, w]^T$ linear velocity in $\mathcal{B}$ frame
v lateral speed in $\mathcal{B}$ frame
$\mathbf{V}_6$ see Eq. (6)
$V_t = \sqrt{u_a^2 + v_a^2 + w_a^2}$ true airspeed
w vertical speed in $\mathcal{B}$ frame
$\mathbf{x} = [\mathbf{v}^T, \boldsymbol{\omega}^T, \mathbf{p}^T, \boldsymbol{\Phi}^T]^T$ state vector
$\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x}_e$ perturbation state vector
$\mathbf{x}_e$ equilibrium state vector
$X_T = T_L + T_R$ engines total thrust

path following principle with trajectory linearization control (Zheng, Huo, & Wu, 2013). Still, most of the nonlinear solutions are only designed for one flight stage.

Another important nonlinear control approach is the gain-scheduling solution. It is perhaps the most popular nonlinear control design technique, widely used in the fields ranging from aerospace to process control (Rugh & Shamma, 2000). In the case of flight control, the gain-scheduling technique evolved since the late World War II for the design of autopilots, being, still today, the prevailing flight control design methodology used to cope with the wide plant variations that occur in the flight aerodynamics (Biannic, Burlion, & Plinval, 2014). Justifying its name, the gain-scheduling controller gains vary according to the current value of a scheduling variable, like airspeed or altitude. The system's operation is divided into different equilibrium conditions, and in each one a fixed control gain is used. If the control parameters are changed at a rate much slower than the slowest time constant of the closed-loop system, the system is stable over the entire operation range as long as the system is stable at each of the operating conditions. Opposed to heavy-lift aircrafts, where the control system has to cope with rapidly varying and nonlinear dynamics induced by large variations of load factors, angle-of-attack or sideslip angles, the airship dynamic is much slower, favoring the use of gain-scheduling techniques based on linear interpolations of static gains. Still, the use of gain-scheduling control applied to lighter-than-air aircrafts is scarcely mentioned in the scientific literature (Masár & Stöhr, 2008; Moutinho & Azinheira, 2008; do Valle, Menegaldo, & Simoes, 2015; Yang & Yan, 2015). Moreover, it is never applied as a single global controller for both lateral and longitudinal motions over the entire flight envelope.

The contributions of this paper are twofold. First, it presents a nonlinear gain-scheduling airship control design methodology encompassing both aerodynamic and hover flight. Different advantages of the single solution proposed are shown and clarified, namely: (i) it simultaneously controls lateral and longitudinal motions, (ii) it is valid over the entire flight envelope, guaranteeing the execution of complete missions, (iii) it is robust to wind disturbances, (iv) it takes into account actuation limitations, and (v) is easy to tune and to implement. Other solutions in the literature answer some of these points as described previously (e.g. the nonlinear backstepping solution presented in Azinheira et al. (2009) addresses points (i)–(iv)), but not all cumulatively.

Second, this paper has a tutorial nature, comprehensively addressing the relevant aspects of such a control design methodology, namely the airship modelling, the dynamics analysis over the flight envelope, and the step-by-step design of a gain-scheduling controller with simulation results that demonstrate the suitability of the approach.