EUCASS 2013, 5th European Conference for Aeronautics and Space Sciences,
Munich, Germany, 1-5 July 2013

Control of Airships in the framework of Optimal Uncertainty Quantification

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Abstract
Trajectory tracking control using Optimal Uncertainty Quantification (OUQ) is proposed in this paper. OUQ gives optimal bounds on the probability of failure in tracking a trajectory when information and assumptions about the system are given. As a case study, control of an airship to track a trajectory is considered in the paper. In controlling the system in tracking a mission trajectory, a rigorous analysis is needed to certify or de-certify a control task. The airship system considered in this paper is based on the concept of Multibody Advanced Airship for Transport (MAAT) and powered by a solar-fuel cell system. It is composed of two main components which are the cruiser and the feeders. The cruiser is always in motion or hovering in the air. The feeders can fly individually for transferring passengers and cargos between the land and the cruiser, or between two cruisers in the air. In this study a model of the airship flight dynamics is developed while considering modelling errors due to uncertainties in simulation of aerodynamic lift, drag, thrust, weight and buoyancy. In this optimization problem, the constraints include the maximum values for the airspeed, flight-path angle, thrust, propulsion power and climb rate. The formulation of OUQ for airship control shows the feasibility of development of airship control system in the frame work of OUQ.

Modeling and control of an airship system requires dealing with many uncertain parameters, of which these uncertain parameters include solar power and wind velocity. The uncertainties in modeling can affect the control tasks (e.g. trajectory tracking or stability) when controlling the dynamic behavior of the system and dealing with uncertain forces such as aerodynamic lift, drag, thrust. Formulation of control strategy in the frame work of Optimal Uncertainty Quantification (OUQ) [1] is proposed here in this paper. Trajectory tracking control in the context of OUQ can give optimal bounds on the probability of failure in tracking a trajectory when information and assumptions about the system are given. Optimal bounds on uncertainties can be defined in terms of the probabilities of deviation from a predefined trajectory or stability at the control design stage, while imposing the optimization constraints. The constraints for this optimization problem can be the maximum values of available power (solar), airspeed (wind velocity) and propulsion power. Control of the airship which deals with uncertainties in modeling in the context of OUQ is presented below.

If $u(t)$ is the displacement vector of the airship, then we define this displacement as

$$u(t) = T\,u_0(t) + v(t) \qquad (1)$$

where $v(t)$ denotes the oscillation of the airship about the desired trajectory path, $u_0(t)$ is the displacement of the coordinate fixed with wind flow (wind-relative displacement), and T is a matrix with arrays of $T_{ij} = 1$ if the ith degree of freedom is a displacement in the jth direction; and $T_{ij} = 0$ otherwise. Substituting (1) into the dynamic equation of the motion of the airship gives

$$M\ddot{v}(t) = \Sigma F(t) - MT\ddot{u}_0(t)$$

where $-MT\ddot{u}_0(t)$ can be considered as the effective forces that causes undesirable oscillation of the airship. It is assumed that the airship is required to remain in a certain level of oscillation in order to satisfy stability criterion and certification. Therefore the certification condition is considered as

$$\|v\|_\infty < C_1,\ \|\dot{v}\|_\infty < C_2 \text{ and } \|\ddot{v}\|_\infty < C_3 \qquad (2)$$

where C_1 is the maximum acceptable displacement deviation from the trajectory, and C_2 and C_3 are the velocity and acceleration limits associated with stability, respectively.

A certification problem in OUQ is defined with constraints on inputs which correspond to the information set available for wind speed w (S for the side wind) and the drag force D. The drag force is characterized by a transfer function ψ. Then $\ddot{u}_0(t)$ can be given by

$$\ddot{u}_0(t) := (\psi * w)(t) \qquad (3)$$

w is the wind velocity vector with random amplitude, direction and duration, which is also independent. Thus is can be considered as

$$w(t) := \sum_{i=1}^{B} X_i w_i(t) \qquad (4)$$

where X_1, ..., X_B are independent random variables with support in $[-\max Q, \max Q]^3$, where Q is the dynamic pressure $Q = \frac{1}{2}\rho(h)V^2$, and the speed of air V is a function of wind velocity w. Components of X_i are $X_{i,1}$, $X_{i,2}$ and $X_{i,3}$. The maximum forces applied to the system based on the dynamic pressure of Q_{max} are

$$\begin{aligned} T_{req} &= Q_{max} U_H^{2/3} C_D \\ L &= Q_{max} C_L(\alpha) \\ S &= Q_{max}\, U_H^{2/3} C_D \end{aligned} \qquad (5)$$

Similarly the maximum power supply by the solar energy to the airship can be obtained based on the maximum available direct normal radiation. The optimal bound on the probability that the airship will be unstable or deviate from the trajectory is the solution of the OUQ problem below [1]

$$\mathcal{U}(A) := \sup_{(F,\mu)\in\mathcal{A}} \mu[F \leq 0]$$

where $\mathcal{A}$ is the set of pairs (F, μ) such that a) F is the mapping of the dynamic pressure $t \longmapsto \ddot{u}_0(t)$ (or solar power) onto the margin min $(C_1 - v)$ by equations (2)-(5). b) μ is probability measure on the wind force excitations defined by (3)-(5) (with $B = 20$)

Reference:

[1] H. Owhadi, C. Scovel, T. Sullivan, M. McKerns and M. Ortiz, "Optimal Uncertainty Quantification," (2010, final version 2012), Accepted for publication in SIAM Review.