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Dynamics modeling and control of a transport aircraft for ultra-low altitude airdrop

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Abstract The nonlinear aircraft model with heavy cargo moving inside is derived by using the separation body method, which can describe the influence of the moving cargo on the aircraft attitude and altitude accurately. Furthermore, the nonlinear system is decoupled and linearized through the input–output feedback linearization method. On this basis, an iterative quasi-sliding mode (SM) flight controller for speed and pitch angle control is proposed. At the first-level SM, a global dynamic switching function is introduced thus eliminating the reaching phase of the sliding motion. At the second-level SM, a nonlinear function with the property of "smaller errors correspond to bigger gains and bigger errors correspond to saturated gains" is designed to form an integral sliding manifold, and the overcompensation of the integral term to big errors is weakened. Lyapunov-based analysis shows that the controller with strong robustness can reject both constant and time-varying model uncertainties. The performance of the proposed control strategy is verified in a maximum load airdrop mission.

1. Introduction

Ultra-low altitude airdrop (ULAA) is an essential capability of a large transport aircraft and it is critical to the success of many military tasks, such as precision delivery of heavyweight equipment and supplies.[1–3] During the standard ULAA operations, materials and goods are released at altitudes of 3–10 m and at aircraft velocities between Mach 0.20 and 0.25 to avoid enemy radar detection and anti-aircraft artillery counteraction.[4,5] Also, the low level and low speed flight characteristics can effectively minify collateral damage risks of the supplies. This is of significance for dropping high-tech equipment that is easy to be damaged or armored vehicles with soldiers on board. To perform perfect airdrop task with precision allocation of the supplies and also to guarantee flight safety, highly steady aircraft dynamics is needed.[6] However, the continuous movement and abrupt out of the heavy cargo can exert large disturbances on the aircraft thus leading to considerable deviation of the aircraft dynamics from the trim position. To hold the flight states, a forward force is required, followed by an abrupt change in the direction of the applied force. The manipulation is quite sophisticated and allows for no margin for operation errors.[7,8] Therefore, research on the control law development of the aircraft for the airdrop mode is necessary and valuable.

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Over recent years, some achievements have been reported in developing advanced aircraft controllers for the airdrop mode. By using linearized model at given operating point, several control methods, including robust control[9] and active disturbance rejection control,[10,11] for the airdrop mode are available in the literature. Although these approaches can improve the performance of the system in different aspects, one shortcoming is that good control performance and robustness are difficult to achieve in the event that the cargo becomes increasingly heavy. In such an event, as mentioned above, the aircraft dynamics can deviate far from the operating point in the traction phase of the airdrop mission. To further improve the performance of the aircraft motion system with strong nonlinearities, many nonlinear control approaches have been developed. The theoretically established feedback linearization method[12] is the one most widely applied.

The system with strong nonlinearities can be decoupled exactly rather than linear approximations by using the feedback linearization method. However, to perform perfect feedback linearization, accurate knowledge of the plant dynamics should be available. This is not the case with the airdrop mode flight control project, since there always exist some unmodeled nonlinear dynamics, such as ground effect.[13,14] Moreover, aerodynamic coefficients obtained from wind tunnel tests, augmented by computational fluid dynamics results, always contain a certain degree of uncertainty. It is well-known that sliding mode control is an efficient approach to deal with model deficiencies and external disturbances. On the basis of feedback linearization of the system, a linear sliding mode controller (LSMC) is designed for the airdrop mode in Refs. [15–17]. Although the operation and stability performance of the system are highly improved, such LSMC approach cannot guarantee global robustness, i.e., the robust tracking is assured only after the system states hit the sliding manifold.

More importantly, the LSMC method faces an unavoidable chattering problem, which might limit its practical application. In order to alleviate the chattering phenomenon, an effective solution is to employ the saturation function instead of the sign function in the control law, thus yielding the concept of quasi-sliding mode control.[18] However, the introduction of the saturation function can lead to a certain degree of steady-state tracking errors in the presence of model uncertainty or external disturbance. This is the disadvantage for the airdrop task. From a practical perspective, high-precision control performance is needed because it can improve not only mission performance but also flight safety. The tracking errors inherited with the quasi-sliding mode controllers can be rejected by introducing an integral function in the sliding manifold.[19,20] A problem of this approach is that the overcompensation of the integral term to big errors can worsen the transient response performance of the system which might further lead to a long convergence time.[21] Note that, to guarantee precision allocation of the supplies and also to improve efficiency of the airdrop mission, good transient response behavior of the aircraft dynamics is required. In these cases, a novel sliding mode control method is called for, which can achieve not only high-precision control performance but also better transient response behavior.

In this paper, a novel sliding mode control method is presented for the airdrop mode. On the basis of feedback linearization of the aircraft-cargo model, a global dynamic sliding manifold is first designed to guarantee the global robust tracking property. To further achieve the high-precision control performance, an integral sliding manifold that iterates based on the first one is designed. Notably, a class of nonlinear function with the property of "smaller errors correspond to bigger gains and bigger errors correspond to saturated gains" is introduced to form the integral term thus yielding better transient response behavior. It is proved that the proposed method can completely reject constant uncertainties and can control the tracking errors to arbitrarily small values under the conditions of time-varying uncertainties. Simulation results verify the good performance of the control system which can meet the airdrop mission performance indexes[8,17] well even in the presence of ±20% aerodynamic coefficients uncertainty, both constant and time-varying type.

2. Aircraft modeling with cargo moving inside

To design a flight controller for the airdrop mode, a reasonable aircraft-cargo motion model of the airdropping process is needed. At present, two types of modeling approaches, including the combination body method[11,17,22] and the separation body method,[7,9,10,16] are available in the literature. The former one takes the aircraft and the cargo as a whole, thus the applied forces between each other are internal actions. The latter one considers the cargo motion as a disturbance to the aircraft and it is convenient for designing controllers. In spite of their strict derivation, a common problem of these modeling approaches is to assume that the cargo moving forward with a known constant acceleration can introduce some degree of model error. In effect, the pitch attitude of the aircraft will rise continuously while the cargo moves along the rail system, and then the component force along the rail of the cargo's gravity also increases continuously. In this case, the acceleration of the cargo can become increasingly big. This fact implies that the model error mentioned above can be enlarged in the event that the cargo becomes increasingly heavy. In this study, the assumptions adopted in Refs. [7,9–11,16,17,22] are relaxed to the following three ones: (1) the aircraft is viewed as a rigid body; (2) the cargo is considered as a particle; (3) the cargo moves along the rail system on the cargo deck, which coincides with the aircraft longitudinal body axis.

Coordinate systems for modeling are illustrated in Fig. 1, which contains the earth frame $Ox_gy_gz_g$, the body-fixed frame $Ox_by_bz_b$ and the track-axes frame $Ox_ky_kz_k$. In Fig. 1, O is the center of gravity (c.g.) of the aircraft, c the c.g. of the cargo, m_b the mass of the aircraft, m_c the mass of the cargo, $\boldsymbol{g}$ the gravity acceleration, α the angle of attack, $\boldsymbol{V}$ the velocity vector, $\boldsymbol{F}^A$ the aerodynamic force vector, $\boldsymbol{M}^A$ the aerodynamic moment vector, $\boldsymbol{F}_c$ the disturbance force vector that the cargo acts on the aircraft, $\boldsymbol{M}_c$ the disturbance moment vector caused by the cargo, $\boldsymbol{T}$ the engine thrust vector, $\boldsymbol{F}_p$ the pull vector which points to the direction of the airflow, φ_p the angle of $\boldsymbol{F}_p$ with

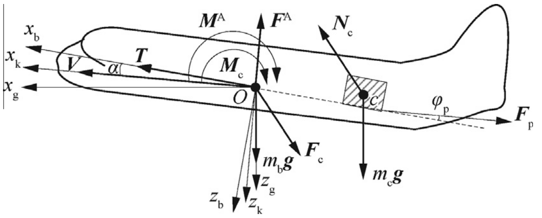

Fig. 1 Definition of coordinates and analysis of forces.