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Compensator-based 6-DOF control for probe asteroid-orbital-frame hovering with actuator limitations

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Abstract

This paper is concerned with 6-DOF control of a probe hovering in the orbital frame of an asteroid. Considering the requirements of the scientific instruments pointing direction and orbital position in practical missions, the coordinate control of relative attitude and orbit between the probe and target asteroid is imperative. A 6-DOF dynamic equation describing the relative translational and rotational motion of a probe in the asteroid's orbital frame is derived, taking the irregular gravitation, model and parameter uncertainties and external disturbances into account. An adaptive sliding mode controller is employed to guarantee the convergence of the state error, where the adaptation law is used to estimate the unknown upper bound of system uncertainty. Then the controller is improved to deal with the practical problem of actuator limitations by introducing a RBF neural network compensator, which is used to approximate the difference between the actual control with magnitude constraint and the designed nominal control law. The closed-loop system is proved to be asymptotically stable through the Lyapunov stability analysis. Numerical simulations are performed to compare the performances of the preceding designed control laws. Simulation results demonstrate the validity of the control scheme using the compensator-based adaptive sliding mode control law in the presence of actuator limitations, system uncertainty and external disturbance.

Keywords: Asteroid-orbital-frame hovering; 6-DOF control; Actuator limitations; Neural network compensator

1. Introduction

The dynamic environments near small bodies (such as asteroids, comets) are perhaps the most strongly perturbed astrodynamic environments found in the solar system. The unique irregular gravitational field in the vicinity of an asteroid yields completely different dynamic environment from the planetary mission, the non-spherical shape of an asteroid can have effect on both the orbital and attitude dynamics of the flying vehicle nearby (Riverin and Misra, 2002). It is of great significance to explore the asteroids for both scientific discovery and human's life. One of the interested close proximity operations to asteroids is hovering, an active control strategy using thrusters in almost continuous mode to null the external effect on the probe, implementing station keeping in the vicinity of an asteroid. Owing to the relatively weak gravitational forces around asteroids, this strategy is feasible for operation. Generally there are two types of hovering over an asteroid: body-fixed hovering and inertial-frame hovering. The body-fixed hovering is suitable for operations very close to the asteroid surface, this kind of hovering is convenient for obtaining high-resolution measurements of a particular area on the asteroid's surface or descent and ascent maneuvers. In inertial-frame hovering, the probe fixes its position relative

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Nomenclature

$o-xyz$	asteroid orbital coordinate system
$o-x_oy_oz_o$	asteroid body-fixed coordinate system
$o_b-x_by_bz_b$	probe body-fixed coordinate system
μ	heliocentric gravitational constant, $\mathrm{m}^3/\mathrm{s}^2$
$\boldsymbol{\rho}$	position vector of o_b relative to o in $o-xyz$, m
ρ	magnitude of $\boldsymbol{\rho}$, m
$\boldsymbol{\omega}$	orbital angular velocity vector of asteroid in $o-xyz$, rad/s
ω	magnitude of $\boldsymbol{\omega}$, rad/s
$\dot{\boldsymbol{\omega}}$	orbital angular acceleration vector of asteroid in $o-xyz$, $\mathrm{rad/s}^2$
$\dot{\omega}$	magnitude of $\dot{\boldsymbol{\omega}}$, $\mathrm{rad/s}^2$
$\boldsymbol{r}_1$	position vector of o relative to the heliocenter, m
$\boldsymbol{r}_2$	position vector of o_b relative to the heliocenter, m
$\boldsymbol{a}_g$	gravitational acceleration vector of asteroid in $o-xyz$, $\mathrm{m/s}^2$
$\boldsymbol{F}_c$	control force vector in $o-xyz$, N
$\boldsymbol{F}_{cb}$	control force vector in $o_b-x_by_bz_b$, N
$\boldsymbol{d}$	external disturbance acceleration vector, $\mathrm{m/s}^2$
$\boldsymbol{F}$	model uncertainty vector in translational motion, $\mathrm{m/s}^2$
m	mass of probe, kg
a	semi-major axis of asteroid's orbit, m
e	eccentricity of asteroid's orbit
n	mean motion of asteroid's orbit, deg/s
f	true anomaly of asteroid's orbit, deg
t	time, s
U	gravity potential of asteroid, N m
μ_a	gravitational parameter of asteroid, $\mathrm{m}^3/\mathrm{s}^2$
C_{20}, C_{22}	normalized second order spherical gravitational coefficients
R_0	normalization radius, m
θ, φ	latitude and longitude of probe in $o-x_oy_oz_o$, deg
R_A^O	rotation matrix that transforms to $o-x_oy_oz_o$ from $o-xyz$
ω_a	spin rate of asteroid, rad/s
i_a	orbit inclination of asteroid, deg
$\boldsymbol{q}$	quaternion vector in $o_b-x_by_bz_b$
$\boldsymbol{\omega}_r$	body rate vector of probe in $o_b-x_by_bz_b$, rad/s
$\boldsymbol{J}$	inertia matrix of probe in $o_b-x_by_bz_b$, $\mathrm{kg}\cdot\mathrm{m}^2$
$\boldsymbol{J}_0$	nominal value of $\boldsymbol{J}$, $\mathrm{kg}\cdot\mathrm{m}^2$
$\Delta\boldsymbol{J}$	uncertain part of $\boldsymbol{J}$, $\mathrm{kg}\cdot\mathrm{m}^2$
$\boldsymbol{\tau}_g$	gravity gradient moment vector in $o_b-x_by_bz_b$, N m
$\boldsymbol{\tau}_c$	control torque vector in $o_b-x_by_bz_b$, N m
$\Delta\boldsymbol{\tau}$	uncertain torque vector in rotational motion, N m
$\boldsymbol{\tau}_d$	disturbance torque vector in $o_b-x_by_bz_b$, N m
$\bar{R}$, $\boldsymbol{C}_P^A$	transformation matrix that transforms to $o_b-x_by_bz_b$ from $o-xyz$
dm	a small mass element of probe, kg
$\boldsymbol{r}$	position vector of dm relative to o_b in $o_b-x_by_bz_b$, m
$\boldsymbol{a}_g'$	gravitational acceleration vector on dm in $o-xyz$, $\mathrm{m/s}^2$
$\boldsymbol{\rho}_b'$	position vector of dm relative to o in $o_b-x_by_bz_b$, m
$\boldsymbol{\rho}_b$	position vector of o_b relative to o in $o_b-x_by_bz_b$, m
$\boldsymbol{u}$	actual control input of 6-DOF dynamic model
$\boldsymbol{v}$	nominal control of 6-DOF dynamic model

to the asteroid in the rotating frame orbiting the sun, creating an artificial libration point in this frame, this kind of hovering can be used as a holding orbit from which to stage other maneuvers or to map the asteroid's surface (Broschart and Scheeres, 2005). Usually this kind of asteroid hovering mission is meant to perform a mapping task or to find a proper opportunity or location for next maneuvers.

Literatures on both kinds of hovering over asteroid have been published recent years. Broschart and Scheeres (2005) investigated the stability of realistic hovering control laws both in the body-fixed and inertial reference frames. A study of hovering orbit control near a non-uniformly rotating small body was presented by Sawai and Scheeres (2001). Then the stability of hovering and translational motion for a probe equipped with an altimeter over a uniformly rotating small body was studied using a simple feedback control by Sawai et al. (2002). The boundedness of spacecraft hovering under dead-band control was discussed in Broschart and Scheeres (2007). Gaudet and Furfaro (2012) formulated hovering problem over small bodies as a Markov decision process, and investigated a reinforcement learning controller with sufficient robustness to allow precision hovering in unknown environments. Kubota (2001) presented a maneuver strategy for station keeping and implementing global mapping around an asteroid. An observer-based hovering control over a tumbling asteroid in the asteroid body-fixed frame was investigated in Nazari et al. (2014). While these papers mentioned above mainly focused on the orbital dynamics and control, the issues about attitude stabilization of probe were not discussed. The attention paid to the attitude dynamics and control is much less than the orbital dynamics and control of a probe in the vicinity of asteroid. Some significant studies on spacecraft orbital mechanics near the solitary small body over the last twenty years were reviewed in Scheeres (2012). By contrast, there are only a few literatures on the rotational motion and control of spacecraft near asteroid. Riverin and Misra (2002) and Misra and Panchenko (2006) discussed the attitude dynamics of a