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A novel nonlinear control for tracking and rendezvous with a rotating non-cooperative target with translational maneuver

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A R T I C L E I N F O

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A B S T R A C T

This paper studies the control of flexible chaser spacecraft to track and rendezvous with a rotating non-cooperative target accompanied by translational maneuver. The problem is formulated that the chaser spacecraft is required to track target position and be synchronized with its attitude precisely. Meanwhile, the elastic vibration, induced by large angular maneuver in the tracking process, needs to be reduced. With respect to this unique movement of target, a novel modified $\theta - D$ control method, derived by standard $\theta - D$ algorithm and *Lyapunov min-max value theorem*, is proposed to incorporate position, attitude and flexural motion into one united control frame. The modification term in the proposed control method is dealt with target translational maneuver, which is the primary contribution in this paper. The asymptotically stability of closed-loop system is proved via the *Lyapunov* theory and *Lyapunov min-max value theorem*. Numerical results demonstrate an excellent tracking performance of proposed united control frame even under large inertia uncertainties.

1. Introduction

On-orbit servicing for non-cooperative target, such as un-functional satellite or spent-aged spacecraft, can help to improve the usefulness, lifespan, resilience and reliability of the target. Specifically, on-orbit servicing plays a significant role in space resource recycling strategy [1–4]. The Challenge arised from in on-orbit servicing for non-cooperative target is accurate position and attitude control in autonomous tracking and rendezvous operation. Since large model uncertainties of chaser and intricate motions of non-cooperative target, therefore a stringent control requirement is needed to impose on accurate position and attitude control of servicing spacecraft [5,6].

Several nonlinear control methodologies and algorithms have been investigated to address this problem. A Linear Quadratic Regulator (LQR) [7] is employed to make a contribution to attitude control of highly flexible spacecraft with time delay. Simulation and experiments validate a good robustness of LQR method to predict model inaccuracies and external disturbance. A sliding mode control method (SMC) [8] can be as a candidate that is applied to the position and attitude tracking control of spacecraft. It had been verified to 6 degree-of-freedom (DOF) control for orbital remover spacecraft. Moreover, SMC also presents a good robustness with respect to bounded disturbances, model uncertainties and measurement errors [9,10]. Owing to multi-step recursive use of higher order term in the *Lyapunov* function, back-stepping control technique [11,12] ensures the global asymptotic convergence of system and achieves a good robustness to parameter uncertainties, leading to a wide application in relative translation and attitude control [13–15]. A coupled synchronization control strategy, based on adaptive feedback linearization approach [16], nullifies relative translation and attitude tracking errors that ensures spacecraft can synchronize with the motion of tumbling target. This coupled controller can be also taken external disturbances and system uncertainties into account. A robust adaptive control algorithm [17] is proved asymptotically stability of closed-loop system errors via *Lyapunov* theory in relative position tracking and attitude synchronization problem. State Dependent Riccati Equation (SDRE) technique is a suboptimal control method [18], implemented to united control of position and attitude. The neural network method can be combined with SDRE to design a robust attitude synchronization control law that is feasible under moment of inertia uncertainties [19,20]. However, the SDRE technique has a difficulty in implementing to higher order system since the Riccati equation has to be solved at every integration step. It should be pointed the controller is required to possess the performance of highly control precision, small control errors and fast online calculation speed due to a strong maneuvering ability of chaser spacecraft in tracking and rendezvous task. A standard $\theta - D$ technique [21–27], a nonlinear integrated position and attitude suboptimal control

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Nomenclature

A	cross section area of solar panel
a_t	unknown translational maneuvering acceleration of target
$\boldsymbol{C}_{bc}^{bc-ref}$	transformation matrix from reference body-fixed frame of chaser spacecraft to its actual body-fixed frame
$\boldsymbol{C}_{ECI}^{bt}$	transformation matrix from body-fixed frame of target to the inertial frame
$\boldsymbol{C}_{c-ref}^{ECI}$	transformation matrix from inertial frame to reference attitude frame of chaser spacecraft
$\boldsymbol{C}_{q_1q_1}, \boldsymbol{C}_{q_2q_2}$	matrix of general damping of chaser spacecraft
E	elasticity modulus
$\boldsymbol{f}_t$	vector of unknown acceleration of target
$\Delta\boldsymbol{g}$	vector of gravity differential term between chaser spacecraft and target
I	second moment of cross section
$\boldsymbol{J}_c$	matrix of moment of inertia of chaser spacecraft without flexible appendage
$\boldsymbol{J}_t$	matrix of moment of inertia of target
J_{cy}	moment of inertia of chaser spacecraft with flexible appendage about spacecraft y_{bc} axis
$\boldsymbol{K}_{q_1q_1}, \boldsymbol{K}_{q_2q_2}$	matrix of general stiffness of chaser spacecraft
L	length of solar panel
$\boldsymbol{M}_{\theta q_2} = \boldsymbol{M}_{q_2\theta}^T$	matrix of inertial coupling term between hub body rotation and transverse elastic deformation
$\boldsymbol{M}_{q_2q_2}$	matrix of general mass of chaser spacecraft
$M_{\theta\theta}$	rotational inertia of chaser spacecraft
$\boldsymbol{Q}_\theta, \boldsymbol{Q}_{q_1}$	matrix of general inertial force of chaser spacecraft
$\boldsymbol{q}_1, \dot{\boldsymbol{q}}_1, \ddot{\boldsymbol{q}}_1$	vector of axial displacement, axial velocity, axial acceleration
$\boldsymbol{q}_2, \dot{\boldsymbol{q}}_2, \ddot{\boldsymbol{q}}_2$	vector of transverse displacement, transverse velocity, transverse acceleration
$\boldsymbol{q}_\delta, \boldsymbol{q}_{\delta-ref}$	vector of attitude error quaternion, reference attitude quaternion
$\boldsymbol{q}_c, \boldsymbol{q}_{c\text{-}ref}$	vector of actual and reference attitude quaternion of chaser spacecraft
$\boldsymbol{q}_t$	vector of actual attitude quaternion of target
q_ε, q_β	sight inclination and declination angle
$q_{\varepsilon-ref}, q_{\beta-ref}$	reference sight inclination and declination
$\boldsymbol{r}_t$	vector of target position defined in inertial frame
r_0	radius of hub rigid body
$\boldsymbol{u}_c$	vector of control acceleration of chaser spacecraft
$\boldsymbol{u}_t$	vector of control acceleration of target
w_1, w_2	axial elongation and transverse bending deflections of chaser spacecraft
$\boldsymbol{\omega}_c$	vector of actual angular velocity of chaser spacecraft
$\boldsymbol{\omega}_{c-ref}$	vector of reference angular velocity of chaser spacecraft
$\dot{\boldsymbol{\omega}}_c$	vector of actual angular acceleration of chaser spacecraft
$\boldsymbol{\omega}_t$	vector of actual angular velocity of target
$\tilde{\boldsymbol{\omega}}_c, \tilde{\boldsymbol{\omega}}_t$	skew matrix of angular velocity of chaser spacecraft and target
$\boldsymbol{\omega}_\delta$	vector of attitude error angular velocity
$\boldsymbol{\phi}_1(x), \boldsymbol{\phi}_2(x)$	modal function vectors of axial and transverse vibration
$\boldsymbol{\tau}_c$	vector of control torque of chaser spacecraft
$\boldsymbol{\tau}_t$	vector of control torque of target
ρ	distance between chaser spacecraft and target
θ_c	rotational angle of chaser spacecraft hub body
Rho	density of solar panel
μ	gravitational constant

method, is designed to improve computational time greatly. This method provides a closed-form approximate solution to the Hamilton-Jacobi-Bellman (HJB) equation through a perturbation process so that control precision improvement and onboard implementations are realized. The standard $\theta - D$ technique [22] has been presented to be vible for relative motion control problem of tracking non-cooperative target but only for the target with rotation motion. Up to data, few has attempted to investigate to integrate the translational maneuver of non-cooperative target with its rotational motion in the position and attitude control problem. In the scope of this paper, we consider the problem of driving a flexible chaser spacecraft (named 'chaser' in the below paragraph) at an arbitrary position to track and rendezvous with a rotating non-cooperative target with a translational motion from far range to close range. A new united control frame is proposed to ensure the chaser tracking to target trajectory, synchronizing with target attitude and reducing elastic vibration of induced by large angular maneuver. Unique features and main contributions in this paper are:

- ☐ A translational motion of non-cooperative target is considered in the control problem of target tracking proximity operation.
- ☐ The motion of flexible structure on the chaser is included in the whole system, and elastic vibration is suppressed in the flight.
- ☐ A new modified $\theta - D$ controller for position, attitude and flexural motion is derived by standard $\theta - D$ technique and *Lyapunov min-max value theorem.* Using *Lyapunov min-max value theorem*, target translational motion is treated as the upper limit of control acceleration introduced into controller The stability of proposed controller is proved via *Lyapunov* analysis and *Lyapunov min-max value theorem.* The effectiveness and accuracy of the proposed is validated through multiple flight scenarioes with model uncertainties.

Rest of this paper is arranged as follows. Section 2 describes motion of equation and problem formulation that includes three mechanical models of flexible chaser: model of relative motion in line-of-sight (LOS) frame, model of flexible chaser spacecraft, model of relative motion coupling flexible chaser spacecraft. The derivation procedure of a modified $\theta - D$ controller combing target translational maneuver is given in detail, and the stability of the close-loop control system is proved in Section 3. Section 4 proposes two simulation scenarios to evaluate the performance of proposed controller. Finally, the conclusive remarks are listed in Section 5.

2. Motion of equation and problem formulation

2.1. Model of relative motion in Line-of-Sight (LOS) frame

As shown in Fig. 1, $O_ix_iy_iz_i$ represents inertial frame is fixed to center of Earth. $O_lx_ly_lz_l$ represents Line-of-Sight frame (LOS frame) that is fixed to mass center of chaser. x_l coincides the tracking sight direction points to non-cooperative target; y_l is in vertical plane which contains x_l; z_l completes the triad. See in Fig. 1. $q_\varepsilon \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, $q_\beta \in (-\pi, \pi)$.

2.1.1. Relative position dynamic formulation

The relative position dynamic equation of flexible chaser spacecraft neglecting gravity is described by Ref. [2]: