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Line-of-sight nonlinear model predictive control for autonomous rendezvous in elliptical orbit

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ABSTRACT

The paper investigates the trajectory planning and control of autonomous spacecraft rendezvous in the orbital plane with line-of-sight dynamics. The control problem, based on nonlinear model predictive control, is formulated in terms of line-of-sight range and azimuth angle. The state feedback with measurement uncertainties is introduced to form a closed-loop optimal control problem by integration of receding horizon strategy. Furthermore, the control input increment instead of total control input is considered in the cost function to generate a smooth transient response. The formulated nonlinear optimal control problem is then transformed into convex quadratic programming problems over the predictive horizon, leading to a computationally efficient algorithm implementable for spacecraft. The numerical results show that the newly proposed line-of-sight nonlinear model predictive control scheme is able to effectively generate optimized approach trajectories with satisfactory control accuracy and the proposed method is insensitive to the measurement uncertainties.

1. Introduction

The increasing population of space debris, such as non-functional satellites or spent upper stages of rocket, poses serious threats to space flight missions [1,2]. To address the threats, active space debris removal has emerged as an appealing strategy for the sustainable use of outer space [3,4]. In such missions, the chaser spacecraft (chaser) has to track the motion of space debris, or a non-cooperative target in general, and then approaches and rendezvouses with the target. Challenges arise in the trajectory planning and tracking control of the chaser, where the chaser is usually required to perform complicated and skewed maneuvers for rapid tracking and station keeping, especially in the proximity operation, to deal with the non-cooperative target.

Many control methodologies and/or strategies have been devoted to generate optimal approaching trajectories to autonomously transfer from one elliptical orbit to another with various objectives, such as, efficient fuel consumption [5], shortest approaching time [6], high control accuracy or robustness [7], subject to operational constraints. Notably, Nonlinear Optimal Control (NOC) has been recognized as one of the most attractive methods to deal with the constrained optimization problems since it optimizes a specific cost function while satisfying the nonlinear equality and/or inequality constraints [8,9]. However, to obtain a feasible solution to the closed-loop NOC in a fast manner is challenging, even for an unconstrained case [10]. Alternatively, Nonlinear Model Predictive Control (NMPC), which is based on receding horizon strategy (RHS) and re-planning of optimal trajectory in real time by solving the NOC at each sampling instant [11,12], has been proved as an effective method [13–16]. The resulting NOC problem can be further reduced to a quadratic programming (QP) problem that is computationally affordable for computers on-board spacecraft.

Autonomous rendezvous with a target in near-field generally employs laser imaging detection and ranging system and advance video guidance system for relative navigation in terms of the relative distance and the Line-Of-Sight (LOS) angles with respect to the target. The aforementioned approaches were based on the Local-Vertical Local-Horizontal (LVLH) formulation [5–7], including the LVLH based NMPC approach [13–16]. As a result, the relative navigation information has to be transformed from the LOS frame to the LVLH frame. The extra transformation between the LOS and LVLH frames complicates the derivation of guidance control and adds extra computational efforts for on-board computers. To reduce the computational requirement for the on-board computers, LOS based autonomous rendezvous were developed to employ the navigation directly [17,18]. The control law was developed based on the phase plane analysis. No attempt has been made to the LOS based NMPC in autonomous spacecraft rendezvous, to the best knowledge of authors.

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Nomenclature

a	semi-major axis of the elliptical orbit
$\boldsymbol{A}(\boldsymbol{X})$	state-dependent system matrix
$\boldsymbol{A}_k$	discretized system matrix at time step k
$\boldsymbol{B}$	control input matrix
$\boldsymbol{B}_k$	discretized control matrix at time step k
e	eccentricity of the elliptical orbit
f	true anomaly of the elliptical orbit
F_ρ, F_θ	control force components along the LOS range and azimuth angle directions
m_c	mass of the chaser
N_c, N	numbers of control horizon and predictive horizon
$\boldsymbol{P}, \boldsymbol{Q}$	weight matrices on the control correction and control error
R_T	distance from the center of the Earth to the target
T_s	sampling time interval
U^{max}	maximum control force
$\boldsymbol{U}$	control input vector
x, y	coordinates of the relative distance vector under orbital frame
$\boldsymbol{X}_d$	desired state vector
$\Delta\boldsymbol{U}_k$	incremental control variable
$\delta\rho, \delta\theta$	measurement errors of LOS range and azimuth angle
θ, θ_d	azimuth angle and desired azimuth angle
ρ, ρ_d	LOS range and desired LOS range
ρ_S	safety distance from the target
$\sigma_\rho, \sigma_\theta$	standard deviations of Gaussian distributions in terms of LOS range and azimuth angle
ω	first order time derivative of the true anomaly

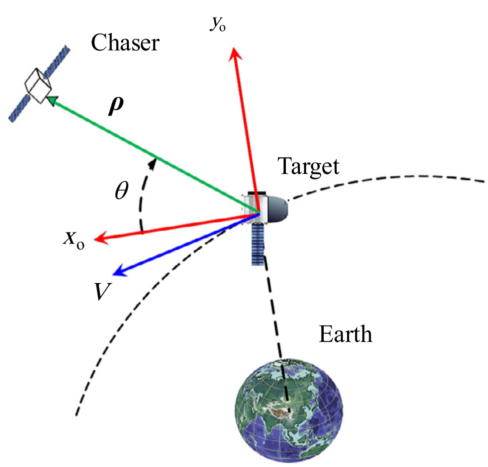

Fig. 1. Schematic of the LOS frame.

In the current work, the autonomous rendezvous is formulated in the LOS frame to directly use the relative navigation information. This intuitive description of the trajectory planning will result in concise formulation of the system dynamics and the controller design, especially for autonomous rendezvous with a passive non-cooperative target.

2. Line-of-sight formulation of spacecraft dynamics

Consider a chaser approaching a target in the orbital plane of an elliptical orbit, as shown in Fig. 1. To focus on the fundamentals of the LOS based NMPC, the current work is limited to the in-plane rendezvous with the target. The orbital frame, shown as $O_o - x_o y_o z_o$ in Fig. 1, is defined with its origin at the Center of Mass (CM) of the target, where the y_o-axis is along the orbital radius of the target, the x_o-axis lies in orbital plane and is perpendicular to the y_o-axis, and the z_o-axis is normal to the orbital plane to complete a right-hand system. The LOS frame is formed by the range ρ and azimuth angle θ with its origin at the CM of the target, where the azimuth angle θ is measured from the x_o-axis in the orbital plane as shown in Fig. 1.

Accordingly, the equations of motion of the chaser in the LOS frame is expressed as per [19],

$$\ddot{\rho} - \rho\dot{\theta}^2 + 2\omega\rho\dot{\theta} + \left[\left(1 - 3\sin^2\theta\right)\frac{\mu}{R_T^3} - \omega^2\right]\rho = \frac{F_\rho}{m_c} \tag{1a}$$

$$\rho\ddot{\theta} + 2\dot{\rho}\dot{\theta} - 2\omega\dot{\rho} - \left(\dot{\omega} + 3\frac{\mu}{R_T^3}\sin\theta\cos\theta\right)\rho = \frac{F_\theta}{m_c} \tag{1b}$$

where $R_T = a(1-e^2)/(1+e\cos f)$ is the distance from the center of the Earth to the target, f denotes the true anomaly, e is the eccentricity, a is the semi-major axis of the target, $\omega = \dot{\delta} = \sqrt{\mu a(1-e^2)}/R_T^2$ and $\dot{\omega} = -2\mu e\sin f/R_T^3$ are the first and second order time derivatives of the true anomaly respectively, μ is the gravitational constant of the Earth, m_c is the mass of the chaser, and F_ρ and F_θ are the force components in the ρ and θ directions of the LOS frame. The detailed derivation of Eq. (1) is given in Appendix.

Introduce the new state vector $\boldsymbol{X} = \{x_1, x_2, x_3, x_4\}^T$ with $x_1 = \rho$, $x_2 = \theta$, $x_3 = \dot{\rho}$ and $x_4 = \rho\dot{\theta}$. Then, Eq. (1) is reduced to a set of first-order differential equations, such that,

$$\dot{\boldsymbol{X}}(t) = \boldsymbol{A}(\boldsymbol{X})\boldsymbol{X}(t) + \boldsymbol{B}\boldsymbol{U}(t) \tag{2}$$

$$\boldsymbol{A}(\boldsymbol{X}) = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \frac{1}{x_1} \\ \omega^2 - \frac{\mu}{R_T^3}(1 - 3\sin^2 x_2) & 0 & 0 & \frac{x_4}{x_1} - 2\omega \\ \dot{\omega} + 3\frac{\mu}{R_T^3}\sin x_2\cos x_2 & 0 & 2(\omega - \frac{x_4}{x_1}) & 0 \end{bmatrix}$$

$$\text{and} \quad \boldsymbol{B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{3}$$

where $\boldsymbol{A}(\boldsymbol{X}) \in \Re^{4\times4}$ and $\boldsymbol{B} \in \Re^{4\times2}$ are the state-dependent system matrix and control input matrix, respectively, and $\boldsymbol{U} = \{F_{x_1}, F_{x_2}\}^T/m_c$ is the control input. It should be noted that the state $x_1 = \rho$ will never approach to zero in practice because the target has finite dimensions.

The control objective of the trajectory planning for an autonomous spacecraft rendezvous is to approach the target with a desired state, $\boldsymbol{X}_d = \{x_{1d}, x_{2d}, 0, 0\}^T$, smoothly to prevent sudden accelerations or decelerations of the chaser.

3. Nonlinear model predictive control

The control objective inevitably leads to an optimal control problem subject to constraint of thrust magnitude. The NMPC, also known as the Nonlinear Receding Horizon Control (NRHC), has been widely used to solve the constrained optimal control problem, due to its advantage of online generation of a set of feedback control commands by iteratively solving an open-loop NOC problem at each sampling instant. The receding horizon process is repeated by shifting the time one-step forward each time [20]. Accordingly, the optimal control problem of the trajectory planning

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