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A novel guidance scheme for close range operation in active debris removal

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ABSTRACT

Active debris removal mission poses new challenge for close range guidance system design because the target debris is uncooperative and uncommunicative. The challenge is particularly critical if the debris is tumbling.

Fly-around phase is an essential component of close range operation and provides precondition for target characterization, inspection and clamp capture. Although related study has been studied in rendezvous and formation flying, technology readiness is still low for application in active debris removal (ADR) and key technology is still under demonstration. Nutation following fly-around is proposed in this paper to define the forced motion which synchronizes chaser with tumbling target. Total synchronization will be necessary for debris capture, e.g. capture by rigid contact robotic arm.

The contribution of this paper is to develop a novel dynamic model governing the relative motion between chaser and target and to design the guidance algorithm. Rotating LOS (Line of Sight) coordinate system is established with origin set at the chaser. Instant Rotating Plane of LOS (IRPL) is introduced to simplify the kinematic equations of tumbling motion based on differential geometric theory. Introduction of IRPL resolves the coupling effect between pitch and yaw planes in general 3D scenario and simplifies the control of chaser with a concise dynamical model.

Two classical cases are presented to illustrate nutation following fly-around and simulations are implemented to demonstrate the effectiveness of proposed guidance scheme. Further study of proximity mission along spin axis is conducted to show the advantages of guidance scheme.

1. Introduction

There are more than 21, 000 tracked objects in space. Among them, only 1600 are functioning satellite and others are space debris. Debris mainly come from uncontrolled spacecraft, lost equipment, rocket stages and disintegration fragments, causing great risks to unmanned- and manned spacecraft in the space. The risk of collision is growing steadily and is of great concern to all satellite operators [1,2]. Active debris removal (ADR) of large non-operational satellites is to meet the urgent need to stabilize the space debris environment. ADR is a cutting-edge mission with large technical challenge in GNC system design. The difficulty lies in that target is uncooperative even with tumbling motion and communication malfunction, which leads to uncertainty in relative motion information [3,4].

Several new technologies are required to implement the ADR mission in different phases, e.g. rendezvous with uncooperative targets, sensor suite and autonomous navigation capability. Close-range operation is an important phase to provide precondition for subsequent capture phase, and close-range operation is generally forced motion, which includes fly-around, hover, and synchronization flight with stable relative position w.r.t capture location.

In order to capture the debris with robotic arm, fly-around operation must be conducted. Its aim is to fly around the target in limited time to observe and characterize debris, which is essential to further operation such as determination of capture appendage and maneuver to pre-determined position, etc. Synchronization flight with target is actually fly-around considering the absolute trajectory w.r.t center of mass (COM), which requires matching target spin period with chaser fly-around period.

Most studies currently focus on the controller design. The synchronous flight problem is taken as a problem of tracking, then

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some specified controller is designed to eliminate the tracking error, e.g. Xin proposed one unified optimal control framework to solve the control of translational, rotational and flexible motions with $\theta - D$ technique [5,6]. Singla studied the application of feedback adaptive controller in autonomous rendezvous ignoring the couplings between relative translation and rotation motion [7]. Sun and Zhang studied the integrated translational and rotational control with 6-DOF backstepping controller or robust adaptive controller [8–10]. Deloo analyzed the rendezvous phase of e.deorbit mission and implement CW equations for free drift phase between impulsive shots [11]. Matsumoto et al [12] develop a fly-by approach for uncontrolled rotating satellite capture on a non-collision path with the solar panels. These nonlinear control algorithms are demonstrated to be effective in regulating proximity operation to tumbling satellite.

As stated, the coupling between translational and rotational motion is a challenge for the control which needs to be tackled in a rigor manner. This is a basic problem of astronautics rather than control problem. However, previous study developed dynamical model using the CW (TH etc.) as the relative position motion equations and quaternion (Modified Rodrigues Parameters etc.) describing relative attitude motion equations. However, it is difficult to determine the size, mass or inertia of tumbling target debris. Consequently, the difference of body coordinates is not available and there would be significant measurement error. So it is a better choice to establish a new relative coordinate system with origin on the chaser.

Then Dual Quaternion is further developed to describe the translation and rotation motion in an integrated manner [13,14]. The relative motion is developed by quantifying the transformation relation of two body coordinates using Dual Quaternion. And the body coordinates are described in inertial frame. The complex algorithm of Dual Quaternion prohibits current mature control algorithms from applying on the controller design as Dual Quaternion is not based on the classical vector operation.

Our previous paper adopts the frame of augmented proportional navigation (APN) to construct a three-dimensional (3D) kinematic equation set in a rotating coordinate system whose origin is set in chaser spacecraft, which has been successfully applied in guidance for mid-range autonomous rendezvous [15]. In APN, classical proportional navigation is applied in the direction normal to LOS and feedback control is introduced along LOS to control relative distance.

Similar to the scheme of APN, a modified guidance scheme is applied to the control of forced fly-around. Different from APN, classical PD controller is applied in transverse direction which is able to control the fly-around velocity and provides a solution for synchronous motion with the tumbling target. Based on the kinematic equation set constructed in a rotating coordinate system, current mature and advanced control algorithms could be applied directly which brings convenience to controller design.

Generally, the sensors like LiDAR could provide target motion estimation in close distance [2]. With such input, the proposed algorithm will be an appropriate guidance algorithm in case of no exact prior knowledge of target orbit from ground sensors.

The 3D guidance scheme is established with introduction of instant rotation plane of the LOS (IRPL) which is able to resolve the maneuvering motion of malfunctioning spacecraft in 3D space. The 3D relative kinematic equations are established in a rotating LOS coordinate system which resolves the coupling effect between pitch and yaw planes in general 3D scenario. Introduction of IRPL simplifies position control of chaser, and the plane of fly-around can be determined by the IRPL. The guidance scheme proposed is concise and rigorous in sense of physics.

This paper consists of 5 sections. Section 2 describes tumbling target motion and the requirement of fly-around mission. In Section 3, the guidance and control algorithm is developed based on the relative kinematic equations constructed in the rotating LOS coordinates. Section 4 shows the simulation results of guidance and control algorithm to demonstrate the effectiveness of guidance scheme proposed. Section 5 summarizes the work of this study. The flowchart of mission design is shown in Fig. 1.

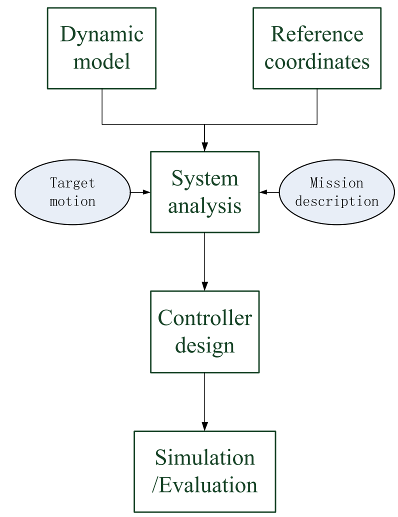

Fig. 1. Framework of mission design.

2. Analysis of mission requirement

This section describes target motion and the requirement of fly-around mission. Before that, the frequently used reference systems are introduced, which lays foundation for flexible guidance and control algorithm.

2.1. Reference system

In previous research, the Local Vertical Local Horizontal (LVLH) coordinate system is commonly used to describe the relative motion between target and chaser, where the origin is located at the target's center of mass, the x axis is along the position vector, the z axis is along the orbit normal, and the y axis completes the right-handed system. However, for fly-around of uncooperative target, it is proper to choose a coordinate system with origin set at the center of chaser.

The relative 3D kinematic equations of LOS were established in Reference [16,17] based on the classical differential geometric curve theory:

$$\begin{cases} \dot{\mathbf{e}}_r = \omega_s \mathbf{e}_\theta \\ \dot{\mathbf{e}}_\theta = -\omega_s \mathbf{e}_r + \Omega_s \mathbf{e}_\omega \\ \dot{\mathbf{e}}_\omega = -\Omega_s \mathbf{e}_\theta \end{cases} \tag{1}$$

where $\mathbf{e}_r$ indicates unit vector along LOS, and $\mathbf{e}_\omega$ is the unit vector of LOS velocity; denoting $\mathbf{e}_\theta = \mathbf{e}_\omega \times \mathbf{e}_r$, $\mathbf{e}_\theta$ is a normal vector of LOS, and then a rotatable coordinate named "LOS rotation coordinate" is established with three orthonormal axes, $\mathbf{e}_r$, $\mathbf{e}_\theta$ and $\mathbf{e}_\omega$. The plane composed by $\mathbf{e}_r$ and $\mathbf{e}_\theta$ is the instantaneous rotation plane of LOS (IRPL); ω_s is the LOS rotation rate, and $\boldsymbol{\omega}_s = \omega_s \mathbf{e}_\omega$. Ω_s is the IRPL rotation rate or the angular velocity of fly-around plane, and $\boldsymbol{\Omega}_s = \Omega_s \mathbf{e}_r$.

The rotating LOS coordinate system and relative dynamic motion are shown in following figures:

Fig. 2 illustrates the relationship between three coordinate systems where subscript A represents inertial frame, subscript s represents ordinary LOS coordinate and $\boldsymbol{e}$ denotes the rotating LOS