Paper

Interception of a free-rotating satellite: an autonomous rendezvous scenario

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Abstract— The spacecraft's lifetime is often limited by reliability and redundancy of its components. Furthermore, serious restrictions on duration of spacecraft operations are posed by finite amount of fuel or cooling agent. It is also clear that once a satellite is launched, it is extremely difficult to replace/modify its hardware on the orbit. Future spacecraft missions, especially huge planetary orbiters, will require servicing support from autonomous unmanned satellites. In this paper we introduce and analyze a new scenario for interception of a free rotating satellite ion a Keplerian orbit. The scenario is divided into several stages to be executed by the servicing satellite: attitude determination of the target object; own motion planning; determination of the optimal target position and orientation before docking; controlled approach, i.e., decreasing of a range between satellites; orbiting of the servicing satellite around the target satellite; docking, i.e., radial degreasing of the intersatellite range till the satellites contact, while keeping constant the relative orientation between them. The control algorithm for the servicing satellite motion during its maneuvers is described. Finally, a few examples of satellite motion simulations according to the proposed scenario are presented.

Keywords— satellite rendezvous, autonomous control systems, docking maneuvers.

1. Introduction

Autonomous rendezvous is a very important element in the retrieval of space payloads (i.e., containerized harvest) or resupply of consumable resources (e.g., gases, fuel, and others) [1, 2]. The scenario of interception of a target satellite by a servicing spacecraft that is introduced in this study deals with a special situation. The target satellite is passive during the rendezvous maneuver, which means that communication between satellites does not exist, attitude control and active thrusters are not available. It corresponds to an event when the satellite is out of control. We assume that the target satellite mechanical parameters (i.e., inertia dyadic, mass) are known and that the satellite is equipped with markers [3, 4] as well as with a docking mechanism [6, 11]. In principle, it is possible to split the autonomous rendezvous into four different subproblems:

- determination of rotational states of both spacecraft by employing a sequence of momentarily orientations;
- optimization of motion during rendezvous with respect to consumed fuel, time of approach, accuracy and reliability of docking;
- planning and controlling the approaching maneuver;
- docking with the help of a robotic arm.

What concerns the spacecraft motion, we assume that initially the satellites follow each other on the same orbit, separated by a distance of 1 km and that the orbit is known with any required accuracy. The rotational motion of the servicing satellite is also known from its on-board attitude control system, but the orientation of the target satellite is to be determined by the vision system on servicing satellite during the rendezvous. Practically, a set of six parameters: three Euler angles and their derivatives have to be found for a given time.

2. Interception scenario

The passive spacecraft S_d is out of control and rotates freely in space, while moving on its approximately Keplerian orbit. The active satellite S_r (servicing spacecraft), should determine the rotational motion of the serviced object and then plan and execute the approach scenario. All operations should be performed autonomously and with minimal expenditure of fuel by the servicing satellite and with a high accuracy of touchdown. The rotational motion of the passive spacecraft is to be determined using a color markers [7].

We assume that S_r periodically (with a frequency of 10 Hz) takes images of S_d in order to identify a set of markers. Then, the onboard computer of S_r determines the six initial parameters of the S_d rotational motion employing a sequence of images. The obtained initial values (at $t = t_0$) are used to predict the future S_d motion. The S_d translational motion follows the simple Kepler equations in U_E frame. The S_r motion is described in the non-inertial U_{Ed} frame, while the control of S_r control will be realized in the orbital coordinate system U_{dorb}. Here, U_E is Earth-centered inertial coordinate system, U_{Ed} results from a parallel translation of U_E to the center of mass of S_d. Similarly, U_d is a S_d body fixed frame, and U_{dorb} is the orbital frame with its origin in the S_d.

The S_r motion is constrained by several factors. The first one is the condition that in the final phase of rendezvous, the relative motion of S_r in the U_d frame should be translational, the second one is a minimum difference between approaching and final velocity. Even before executing the approaching maneuver, the first approximation of the optimal solution can be found:

$$\begin{bmatrix} \vec{r}^{\,opt}_{\alpha 0,dorb} \\ \vec{v}^{\,opt}_{\alpha 0,dorb} \end{bmatrix} = \min_{v}\left[\min_{r}\left[\begin{matrix} \left|\vec{r}_{\alpha 0,dorb;x}(t)\right| \\ \dfrac{d\vec{r}_{\alpha,dorb}(t)}{dt} - \vec{v}_{\alpha 0,dorb}(t) \end{matrix}\right]\right] \rightarrow t_{s\_opt} < t < t_{f\_opt}, \tag{1}$$

where r describes position vector in mentioned frame respectively, v – represents its time derivates in a specified time-range.

In the first step (Fig. 1), the translational part of motion can be planned, and later executed, by linking the initial

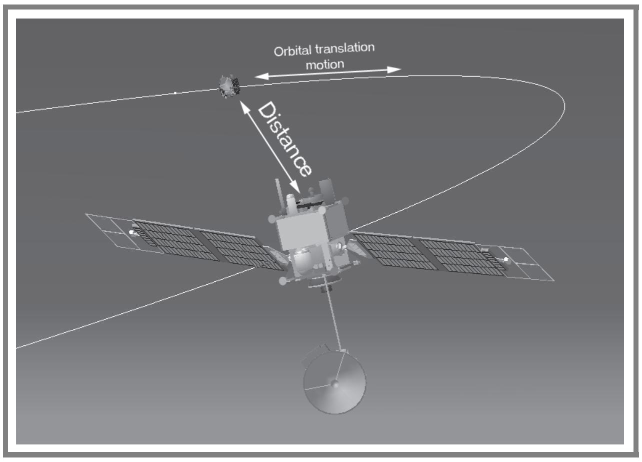

Fig. 1. First step of maneuver.

and final point Eq. (1) in the phase space. During the motion, new initial values of S_d motion are calculated first, then rotational motion is predicted and finally a new optimal solution is calculated from the condition of a minimum

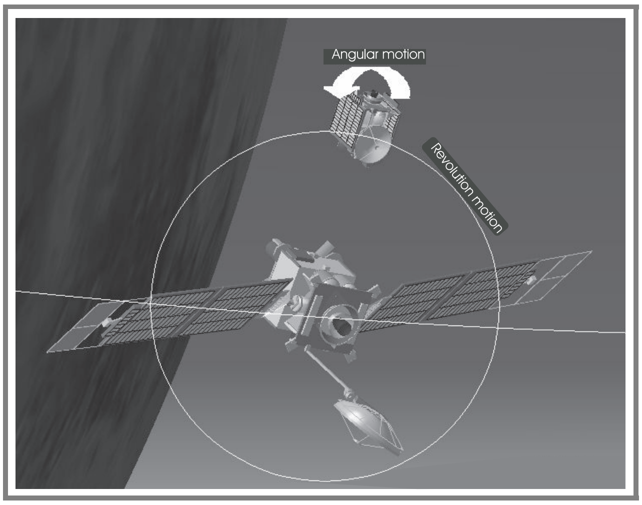

Fig. 2. Third step of maneuver.

difference between the new final state and the previous optimal solution Eq. (1).

In the next step, also the rotational motion is considered. The time dependence of Euler angles and angular velocity vector, as they change during the motion, can be derived from known initial and final angular positions and velocities. We follow the same approach as it was used in first step for planning the position and velocity change.

The third step (Fig. 2) is simply a synchronous orbital motion of S_r around S_d on a circle with a radius $|r_{\alpha 0,d}|$. We arbitrarily assume that half of the rotation cycle is executed before the docking operation is initiated.

In the fourth and final step (Fig. 3) S_r is decreasing its distance with respect to S_d. When observed from U_d (i.e., the coordinate system rotating with S_d), the motion of S_r is translational, i.e., the servicing spacecraft approaches S_r in radial direction. On the other hand, in U_{dorb} the trajectory is a spiral with an outer and an inner radii equal to $|r_{\alpha 0,d}|$ and $|r_{\alpha f,d}|$.

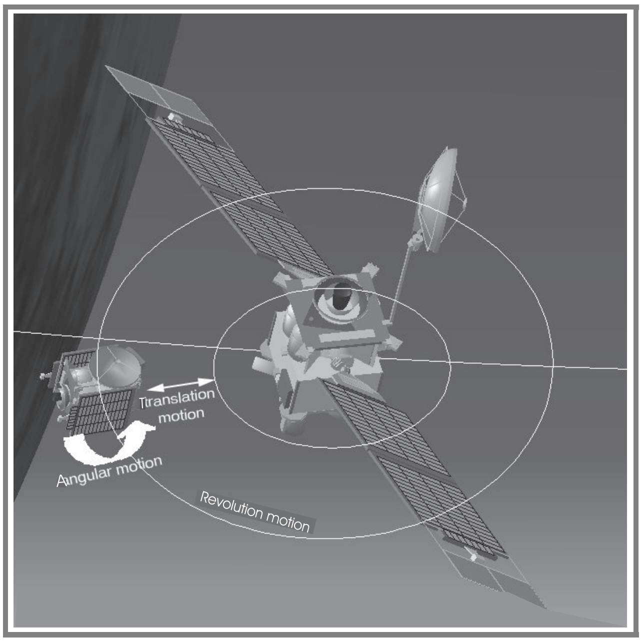

Fig. 3. Fourth step of maneuver.

The control system is taken from [5]. The mathematical description of the translational and rotational motion with a controlling term included is given by the expression (2) and (3). The numerical results have been performed using MATLAB, Simulink 6.0 and Aerospace Blockset 1.6 toolbox. This adds reliability to the proposed approach:

$$\ddot{r}_\alpha + \frac{\mu \cdot r_2}{|r_2|^3} = \frac{\mu \cdot r_1}{|r_1|^3} + \frac{F_c(t)}{m_S}, \tag{2}$$

$$I_S \dot{\varpi}_S + \varpi_S \times (I_S \cdot \varpi_S) = M_c(t), \tag{3}$$

where in Eq. (2) r_2 is the position of S_d in U_E, $r_\alpha = r_2 - r_1$ is the position of S_r in U_{Ed}, $F_c(t)$ – the controlling force

Table 1
Simulations parameters

Satellite	Initial orientation [rad]	Initial rate [rad/s]	Mass [kg]	Interia tensor [$kg \cdot m^2$]	Total time of simulation [s]	Time for optimization $T\left((t\_\{sopt\},t\{fopt\}\right)$	Camera frequency [Hz]
Target (passive)	(0.5,0.01,0.2)	(0.3,0.2,0.1)	2366	diag(4069,12030,11029)	500	(260,370)	10
Service (active)	(0,π/4,0)	(0,0,0)	189	diag(13,38,35)			

of S_r motion, and in Eq. (3) ω is angular velocity of S_r, $M_c(t)$ – the controlling torque of S_r motion, m_s – mass of satellite S_r, and I_s – inertia dyadic of satellite S_r.

3. Simulation example and conclusions

The simulation results for a specific approach are presented in Fig. 4. The simulation includes all maneuvers considered in the scenario:

- translational motion;
- adjustment of rotational motion;
- orbiting over S_d;
- spiraling to a close distance.

The computations were performed using Runge-Kutta (ode45) procedure. The servicing and target satellites are in the same orbit: altitude 200 km with zero inclination and

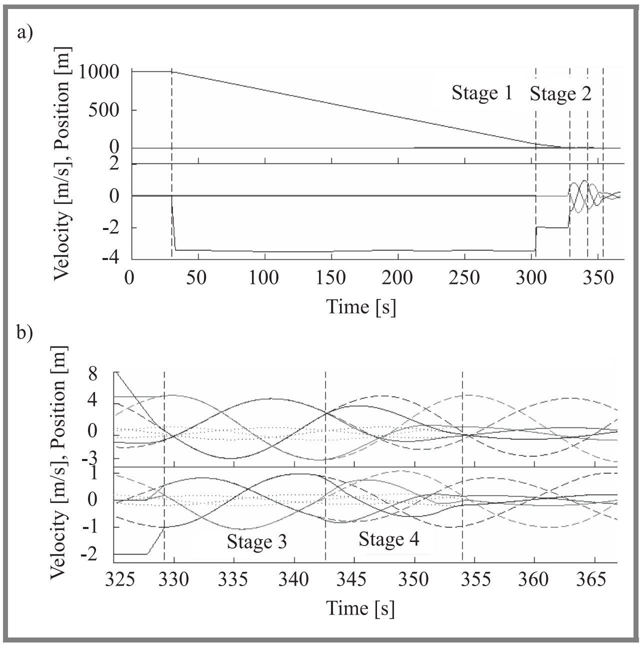

Fig. 4. Position and velocity of service satellite during approaching maneuver: (a) stages 1 and 2; (b) stages 3 and 4.

distance between satellites equal to 1 km. The simulation parameters are listed in the Table 1.

The servicing satellite (S_r), before starting the approaching maneuver, analyzes rotational motion of the target satellite (S_d) and determines its orientation [3, 4]. Then, it calculates the approaching trajectory and starts to realize it. In Fig. 5 the estimation error of Euler angles as determined by the S_r vision system is shown. During the maneuver, the final position is iteratively corrected.

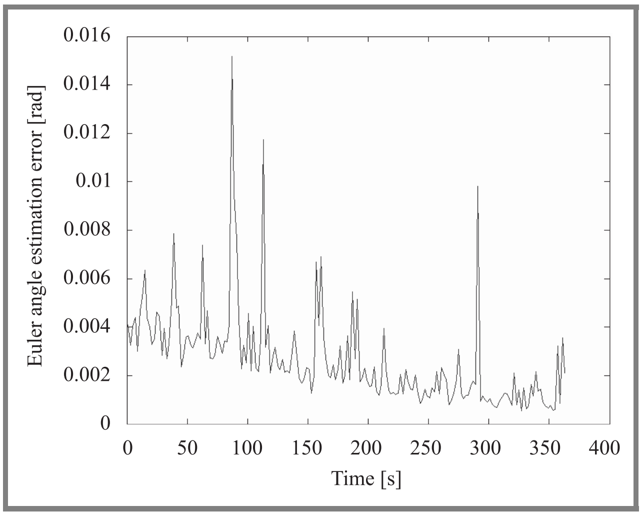

Fig. 5. Standard deviation of estimated error of Euler angles.

In Fig. 4 the trajectory and velocity during stage 1–4 is presented with fine resolution. The rendezvous position (in the end of stage 2) is optimal from the point of view of fuel consumption. In the stage 3, the position of (S_r) (solid line) with respect to the target satellite (dashed line) is constant and the distance between the object is equal to 5 m. In the stage 4, the spiral motion of S_r toward S_d is executed. In the rightmost part of the plot S_r (solid line) approaches the target satellite to a distance of 1 m (dotted line).

The plots in Fig. 6 show the corresponding result for the rotational motion. The solid line represents Euler angles (φ, θ, ψ) and angle-rate (p, q, r) of S_r, respectively, and the dotted line describes the same parameters for S_d. In the stages 3 and 4 these parameters are the same for both satellites. The obtained accuracy of the whole maneuver is about 6 cm.

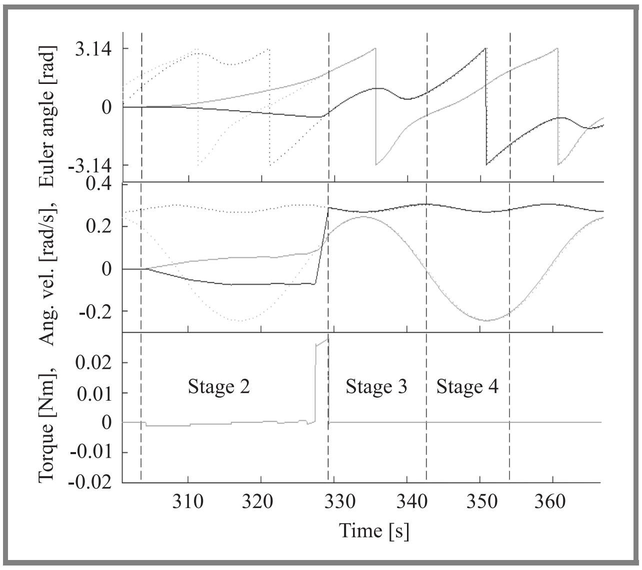

Fig. 6. Orientation and angular velocity of service satellite during approaching maneuver.

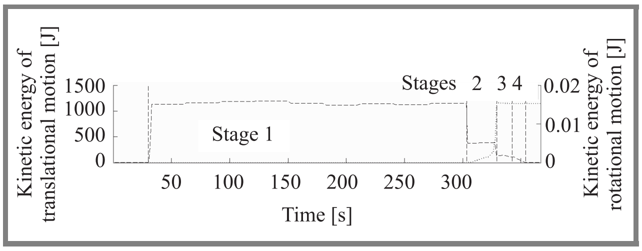

Fig. 7. Kinetic energy of translational (left axes) and rotational (right axes) motion.

The last plot (Fig. 7) presents the kinetic energy of S_r as it changes during the rendezvous. The right part (dotted line) corresponds to the rotational motion, while the left one to the translational motion (dashed line).

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