Study on Forced Straight-Line Guidance for the Final Translation Phase of Spacecraft Rendezvous

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Abstract: Aimed at the problem of final translation of space rendezvous for the applications such as docking, inspection and tracking, optimal straight-line guidance algorithm based on pulse/continuous low-thrust in the context of Clohessy-Wiltshire dynamics is proposed. Two modes of guidance strategy: varying-speed and fixed-speed approaching scheme for V-bar and R-bar approach by using constant/finite low-thrust propulsion respectively are studied, and the corresponding fuel-optimal conditions are obtained. Numerical simulation is conducted to verify and test the proposed algorithms. The results show that there is generally no different between the fuel consumptions by using the two different approaching modes for V-bar case. However, the conclusion for R-bar case is different that the using of continuous low-thrust cost more fuel and transfer time.

Keywords: Space rendezvous, final translation, straight line guidance.

1 Introduction

The final translation phase is the last stage of rendezvous and docking, and also the most critical stage. Because the relative navigation equipment used in final translation phase is mainly optical sensors of high-precision and narrow view field (such as CCD cameras, sight sensor of rendezvous, etc. [Rems, Risse and Benninghoff (2017); Ardaens and Gaias (2018)]), it is required that the target is always in the field of view of optical sensor, and the relative navigation information output continually [Zhu, Yin and Tang (2005)]. Usually, the chaser is forced to move to the target along the quasi-straight line in the approaching corridor. Furthermore, in order to ensure the safety of rendezvous and docking, there are some requirements on the relationship of the changing of relative velocity with relative distance in this phase, that is, the relative velocity should gradually decrease to the desired level until docking in a certain time, in accordance to exponential mode or constant speed mode and others. Therefore, the development of the straight line guidance law for the final translation phase is significant for practical engineering problems.

The straight line guidance law for the final translation phase is contained by V-bar and R-bar guidance. An R-bar straight line guidance law of the combination of impulsive and

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continuous thrust was studied by Fehse [Fehse (2003)], but this method also requires pulse output function of a thruster, which is difficult to achieve for large spacecraft. A multi-pulse glideslope guidance algorithm based on straight line trajectory approximation was proposed by Hablani et al. [Hablani, Tapper and Dana-Bashian (2002)], which can make the relative velocity decreasing exponentially with the increase of the relative distance. Unfortunately, the speed pulse obtained is continuous, which is sometimes unfeasible in engineering implementation, and the guidance of "jump" type would pose a potential risk of security. A potential function guidance algorithm was presented by Olcayto et al. [Olcayto, Ender, McInnes et al. (2007)], which can enable the chaser to approach the target safely. However, the terminal precision of potential function guidance developed by Zhang [Zhang (2010)] is quite low. Proximity guidance strategy of exponential decay type, constant type, and segmented type was discussed by Zhu et al. [Zhu and Yin (2004)], wherein the author merely focused on the design method from macroscopic not analysis specific issues in-depth. The multi-pulse glideslope guidance method was achieved through the propeller thrust's multiple switches equivalent to the variable thrust by Zhang [Zhang (2007)], but this method requires a frequent switching operation of the thrust. V-bar and R-bar Glideslope Guidance Algorithms based on Linear Programming Approach was proposed by Ariba et al. [Ariba, Arzelier, Urbina et al. (2016)], where online computational resources for optimization are required. Model predictive control algorithm based on line-of-sight measurement was studied by Li et al. [Li and Zhu (2017)], where also the computational burden is heavy. Low thrust minimum time transfer based on iterative method was presented by Koblick et al. [Koblick, Xu, Fogel et al. (2016)].

The objective of this paper is to develop an optimal approach guidance algorithm for the final translation phase of space rendezvous and docking by using continuous low-thrust is studied, which expands the straight line guidance concept in Fehse et al. [Fehse (2003); Gong and Luo (2013)] and segment guidance strategy in Li et al. [Li and Zhu (2017)]. The optimal guidance law for the V-bar and R-bar approach by using continuous low-thrust is developed, based on Clohessy-Wiltshire equations [Clohessy and Wiltshire (1960)]. Finally, numerical simulations verify the accuracy, efficiency of the proposed methods. While contributions due to J_2 and higher-order gravity terms, atmospheric drag, solar radiation pressure are important, these effects are specific to spacecraft orbit selection, mass and geometry, which is beyond the scope of this paper.

The relative motion dynamics and problem statement are presented in Section 2. Analytic guidance law for V-bar forced straight-line rendezvous is presented in Section 3 while that for R-bar is presented in Section 4. Numerical simulations and result analyses are presented in Section 5. Conclusions are presented in Section 6.

2 Relative motion dynamics and problem statement

2.1 Relative motion dynamics

Under the assumption of the two-body problem and the distance between the chaser and target is small compared to the distance of the target to the center of the Earth, the relative motion between two spacecraft that is applicable to eccentric orbit can be modeled in the Local vertical local horizontal (LVLH) frame of the target and governed by

$$\begin{aligned}&\ddot{x}-2n\dot{z}-n^2x-\dot{n}z+\frac{\mu}{R_T^{\ 3}}=f_x\\&\ddot{y}+\frac{\mu}{R_T^{\ 3}}y=f_y\\&\ddot{z}+2n\dot{x}-n^2z+\dot{n}x-\frac{2\mu}{R_T^{\ 3}}z=f_z\end{aligned} \tag{1}$$

where x, y and z are the relative position of the chaser relative to the target. Moreover, z-axis points to the nadir direction (also named R-bar), y-axis is normal to the orbital plane and opposite to the angular momentum vector (H-bar), and x-axis completes the orthogonal set (V-bar); f_x, f_y and f_z are the acceleration components acting on the chaser in the x, y, z frame; n is the average orbital rate of the target; R_T is the radius of the target orbit which can be approximated by the radius of the chaser orbit; μ is the gravitational parameter. Additionally, the origin of the rotating LVLH reference frame is co-located with the target center-of-mass.

When the target is flying in the near-circular orbit, Eq. (1) can be reduced to the well-known Clohessy-Wiltshire equations in Clohessy et al. [Clohessy and Wiltshire (1960)].

$$\begin{aligned}&\ddot{x}-2n\dot{z}=f_x\\&\ddot{y}+n^2y=f_y\\&\ddot{z}+2n\dot{x}-3n^2z=f_z\end{aligned} \tag{2}$$

Since this paper is trying to solve the guidance problem for near-circular orbital rendezvous and docking, Eq. (2) will be used to model the relative motion in the rest of the paper.

2.2 Problem statement

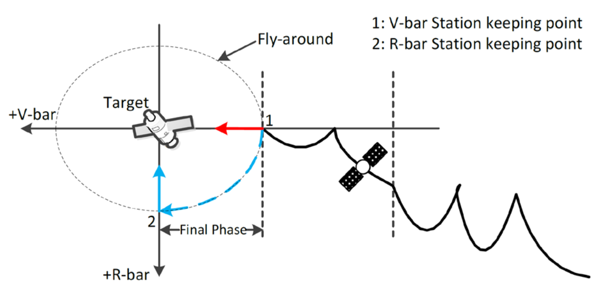

Figure 1: Space rendezvous progress and the docking modes of final phase

Generally, a whole rendezvous and docking of spacecraft includes several main progress: far-range rendezvous, mid-range rendezvous, and final phase. It is common that the final phase is made up of station keeping, fly-around and straight-line translation as shown in Fig. 1. Before the starting of the final translation, station keeping is usually conducted on V-bar or R-bar direction. If the docking port points to the R-bar direction, the chaser is required to fly around the target from berthing point 1 to berthing point 2. A fly-around algorithm could be found in Woffinden [Woffinden (2008)]. In this manuscript, the emphasis focuses on the translational motion guidance for the final phase of docking from the perspective of dynamics, where both V-bar and R-bar approaching methods are included.

3 Analytic guidance law for V-bar forced straight-line rendezvous

When the chaser starts to approach the target from the berthing point along the V-bar direction, the expected situation is that there is velocity along the x-axis, while for y- and z-axes there should be no velocity. Following section is based on the v_x characteristics to investigate two approaching modes, namely, the impulse thrust mode with fixed approaching speed, and the continuous thrust mode with variable approaching speed.

3.1 Fixed-speed approaching

When the chaser applies the constant speed v_x for approaching the target along the V-bar direction, the simplest motion is the two-pulse guidance movement in the X-axis direction. To achieve this, at the starting point x_0, a pulse Δv_{x_1} is thrusted to the chaser, which makes it has the velocity of v_x. Then, at the terminal location x_d, another reverse pulse Δv_{x_2} is imposed which is the same amount as the Δv_{x_1} to decelerate the chaser. The relative orbit for this guidance scheme is the well-known Hopping trajectory as shown in the left part of Fig. 2.

However, hopping trajectory is not safe for the docking phase because of a navigation error, thrust error, and other potential uncertainties. Thus, the straight line approach is required. Then, a simple way is to modify the two-pulse guidance algorithm that using continuous low-thrust to counteract the hopping motion, i.e., forced straight movement. Therefore, to ensure that the chaser has no movement along the z-axis, continuous forces are required to be applied along the z-axis, as shown in the right subfigure of Fig. 2.

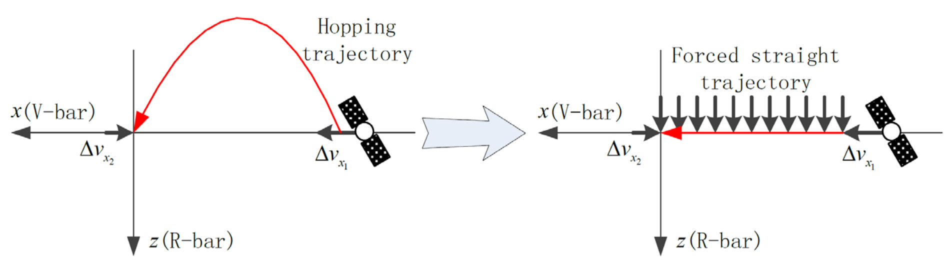

Figure 2: Straight V-bar guidance schematic diagram

Following this assumption, the relative state of the chaser concerning the target at the berthing point is:

$$x = x_0, y = z = \dot{x} = \dot{y} = \dot{z} = 0 \tag{3}$$

Then, a controlled velocity Δv_{x_1} can be conducted to the chaser along V-bar direction

$$\dot{x}(0) = \Delta v_{x_1} = v_x \tag{4}$$

Next, the chaser's relative motion in the X-axis within the range of $x(t) \in [x_0, x_d]$ can be formulated as follows:

$$x(t) = x_0 + v_x \cdot t \tag{5}$$

According to the C-W dynamics, with the previous initial condition, to ensure that the chaser has no relative motion along the z-axis, all we need is to make its control force f_z to satisfy the following equation

$$f_z = 2nv_x \tag{6}$$

Additionally, another reverser velocity Δv_{x_2} will be executed to stop the chaser at the target point. Therefore, the entire velocity pulses consumption in the translation from position x_0 to x_d can be achieved by

$$\Delta V_{total} = \left|\Delta v_{x_1}\right| + \left|f_z \cdot \Delta t\right| + \left|\Delta v_{x_2}\right| \tag{7}$$

where $|\cdot|$ stands for 2-norm operator, Δt denotes the transfer time which can be calculated by $\Delta t = \Delta x / v_x$.

Then, by combining Eqs. (3)-(6) and substituting into Eq. (7) yields

$$\Delta V_{total} = \frac{2\Delta x}{\Delta t} + 2n\Delta x \tag{8}$$

Obviously, the propellant consumption of using the constant speed V-bar approaching would rapidly decrease with the increasing of the transfer time, which means the propellant consumption of the chaser has a linearly increasing relationship with its average approaching velocity. The minimum propellant consumption in the ultimate situation is $2n\Delta x$, which can be seen in Fig. 3.

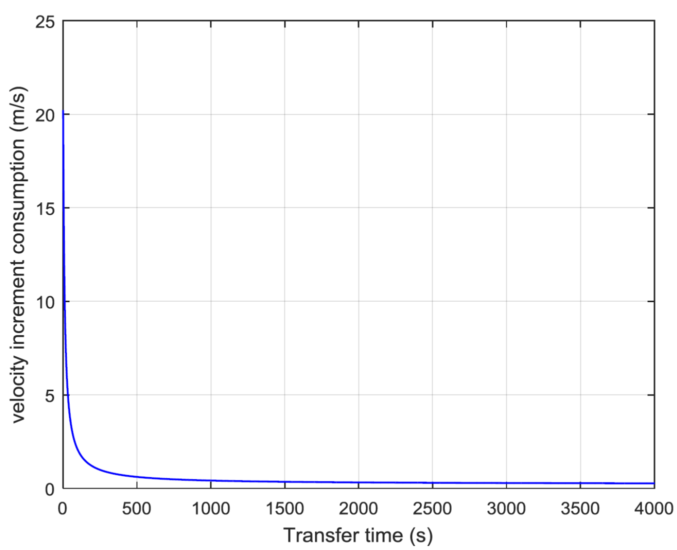

Figure 3: Fuel consumption with transfer time for V-bar approach with constant speed

3.2 Varying-speed approaching

Due to the limitation of the thruster, the speed of the chaser cannot be changed a lot instantaneously. There will be an accelerating or decelerating process. Therefore, for V-bar approaching, the speed is also a variable number. The assumed initial condition is formulated as follows:

$$x(0) = x_0 \tag{9}$$

while other state components are zeros.

The motion equation in x-axis within the range of $x(t) \in [x_0, x_d]$ can also be modeled

$$x(t) = x_0 + \int_{t_0}^{t} v_x(\tau)\,\mathrm{d}\tau \tag{10}$$

Considering the chaser is in a constant thrust mode, it performs the uniform acceleration, uniform speed and uniform deceleration. Therefore, the x-axis velocity $v_x(t)$ of the chaser is required to meet the following conditions

$$v_x(t) = \begin{cases} \dfrac{F_x}{M} \cdot t & t_0 < t \le t_1 \\ V & t_1 \le t \le t_2 \\ V - \dfrac{F_x}{M} \cdot (t - t_2) & t_2 \le t \le t_2 + t_1 \end{cases} \tag{11}$$

where F_x is propeller thrust along V-bar direction while M is the mass of the chaser, V denotes the speed during the phase of uniform approaching, t_1 is the ending epoch for the acceleration, while t_2 is the starting epoch for deceleration. t_1 and t_2 can be calculated as follows:

$$t_1 = \frac{VM}{F_x}, t_2 = \frac{\Delta x}{V} \tag{12}$$

Then, to ensure the chaser is forced to head to the target all the time, a control force acceleration along z-axis, f_z, is required to be executed

$$f_z(t) = 2nv_x(t) \tag{13}$$

As result, the total fuel consumption for forcing the chaser approaching the target along Vbar direction from x_0 to x_d can be modeled as follows:

$$\Delta V_{total} = \left|\Delta v_{x_1}\right| + \int_0^{t_1+t_2} \left|f_z\right| dt + \left|\Delta v_{x_2}\right| = 2|V| + 2n\int_0^{t_1+t_2} \left|v_x(t)\right| dt \tag{14}$$

Next, substituting Eqs. (9)-(13) into Eq. (14) yields

$$\Delta V_{total} = 2V + 2n\Delta x \tag{15}$$

Obviously, the total fuel consumption of the chaser is linearly related to the biggest approaching speed. In other word, longer transfer time means less fuel consumption. The limitation of the minimum consumption is $2n\Delta x$, which is as same as that of Fixed-speed approaching case shown in Subsection 3.1.

4 Analytic guidance law for R-bar forced straight-line rendezvous

In some cases, the chaser is required to approach the target along the R-bar direction, starting from the berthing point. It is expected that the chaser only moves along the z-axis direction, but not in the x and y axes directions. According to the characteristics of the thrust, the guidance law of impulse thrust mode with constant approach speed and finite thrust mode with variable approach speed would be investigated in the following subsections.

4.1 Fixed-speed approaching

The easiest way to realize the movement is by using two-pulse guidance method where a pulse Δv_{z_1} in the direction of R-bar is imposed to the chaser on the starting epoch and then another reverse pulse Δv_{z_2} is executed on the final epoch. This two-pulse guidance is also named sliding guidance. However, the sliding guidance is a drifting mode during the two pulses which cannot satisfy the requirement of safety of the rendezvous for the final phase. Thus, continuous forces are required to be performed on the chaser during the epochs between the two-pulse, as shown in Fig. 4.

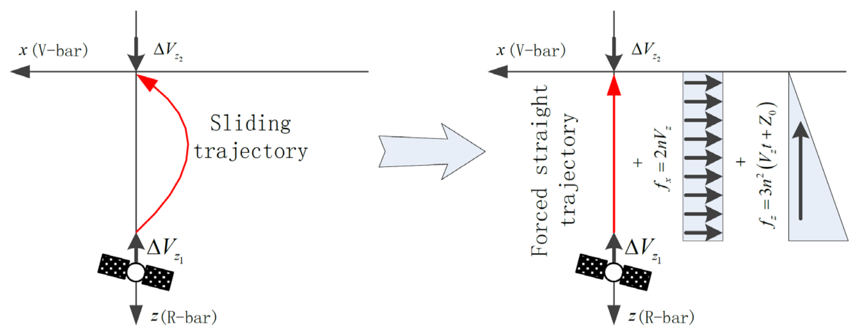

Figure 4: Straight R-bar guidance schematic diagram

Let the initial position be at the berthing point that has z_0 offset from the original point along R-bar direction. After imposed on a velocity pulse v_{z_1}, the initial state of the chaser is

$$\begin{aligned} &x(0) = y(0) = \dot{x}(0) = \dot{y}(0) = 0 \\ &z(0) = z_0, \dot{z}(0) = v_{z_1} \end{aligned} \tag{16}$$

According to C-W equations shown in Eq. (2), if the control force acceleration performed on the chaser along x-axis and z-axis satisfy the following equations

$$f_x = -2nv_z, f_z = -3n^2\left(v_z t + z_0\right) \tag{17}$$

the solution of the C-W equations would be

$$\begin{cases} x(t) = y(t) = \dot{x}(t) = \dot{y}(t) = 0 \\ z(t) = z_0 + v_z \cdot t \\ \dot{z}(t) = v_z \end{cases} \tag{18}$$

Obviously, the chaser would approach the target along R-bar direction with a constant speed. Then, the total fuel consumption for the translation from z_0 to z_d would be

$$\Delta V_{total} = \left|\Delta v_{z_1}\right| + \left|f_x \cdot t\right| + \left|f_z \cdot t\right| + \left|\Delta v_{x_2}\right| \tag{19}$$

Substituting Eqs. (16)-(17) into Eq. (19) produces

$$\Delta V_{total} = \frac{2\Delta z}{\Delta t} + 3n^2\left(0.5\Delta z + z_0\right)\Delta t + 2n\Delta z \tag{20}$$

where $\Delta z = z_d - z_0$ denotes the displacement and Δt is the expected transfer time.

For a given z_0 and Δz, the fuel consumption of the R-bar approach with a uniform speed state decreases and then increases with the evolving of transfer time, as shown in Fig. 5.

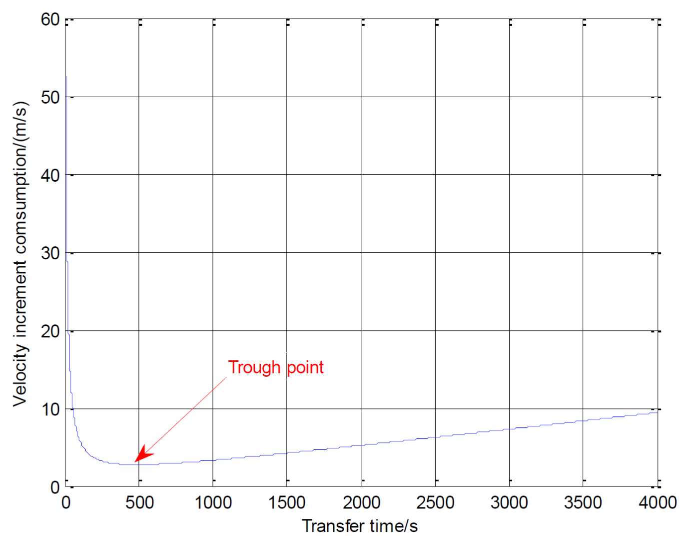

Figure 5: Fuel consumption with transfer time for R-bar approach with constant speed

Then, the optimal transfer time for a minimum fuel consumption can be achieved by calculating the derivative of formula (20) and setting to zero

$$\Delta t = \frac{1}{n}\sqrt{\frac{2\Delta z}{1.5\Delta z + 3z_0}} \tag{21}$$

and the corresponding minimum fuel is

$$\Delta V_{total} = 2n\left(\sqrt{3\Delta z^2 + 6z_0\Delta z} + \Delta z\right) \tag{22}$$

4.2 Varying-speed approaching

For the case of finite thrust, the chaser's velocity cannot be changed abruptly. There would an acceleration or deceleration process, so the velocity of R-bar approaching is varying. Thus, the R-bar guidance law with variable velocity in the case of finite thrust is studied in this subsection.

The motion equation in z-axis direction within the range of $z(t) \in \left[z_0, z_d\right]$ is

$$z(t) = z_0 + \int_{t_0}^{t_1} v_z(t)\,dt \tag{23}$$

where $v_z(t)$, the approaching speed, is defined as follows:

$$v_z(t) = \begin{cases} \dfrac{F_z}{M} \cdot t & t_0 < t \le t_1 \\ V & t_1 \le t \le t_2 \\ V - \dfrac{F_z}{M} \cdot (t - t_2) & t_2 \le t \le t_2 + t_1 \end{cases} \tag{24}$$

where F_z is the thrust of the propeller in z-axis direction, t_1 and t_2 can be calculated as follows:

$$t_1 = \frac{VM}{F_z}, t_2 = \frac{\Delta z}{V} \tag{25}$$

Similarly, if the accelerations imposed on the chaser along the direction of x-axis and z-axis, f_x and f_z meet the following conditions, there will be no drifting in x-axis and z-axis.

$$\begin{cases} f_x = -2nv_z \\ f_z = -3n^2 (v_z t + z_0) \end{cases} \tag{26}$$

Then, the total velocity consumption used to translation from z_0 to z_d is

$$\Delta V_{total} = \left|\Delta v_{z_1}\right| + \int_0^{t_1+t_2} \left|f_x\right| dt + \int_0^{t_1+t_2} \left|f_z\right| dt + \left|\Delta v_{z_2}\right| \tag{27}$$

Substituting Eqs. (24)-(26) into Eq. (27) yields

$$\Delta V_{total} = \left[\frac{3n^2 M}{F_z} \left(\frac{\Delta z}{2} + z_0 \right) + 2 \right] V + \frac{3n^2 \Delta z \left(\dfrac{\Delta z}{2} + z_0 \right)}{V} + 2n\Delta z \tag{28}$$

Apparently, the total fuel consumption for a given displacement Δz and initial offset Z_0 would decrease firstly and then increase while the biggest transfer speed increases, as shown in Fig. 6.

Similarly, the speed condition for a minimum fuel consumption can be achieved

$$V = \sqrt{\frac{3n^2 \Delta z \left(\dfrac{\Delta z}{2} + z_0 \right)}{\dfrac{3n^2 M}{F_z} \left(\dfrac{\Delta z}{2} + z_0 \right) + 2}} \tag{29}$$

and the corresponding fuel consumption is as follows:

$$\Delta V_{total} = 2n \left(\sqrt{3\Delta z \left(\frac{\Delta z}{2} + z_0 \right) \left(\frac{3n^2 M}{F_z} \left(\frac{\Delta z}{2} + z_0 \right) + 2 \right)} + \Delta z \right) \tag{30}$$

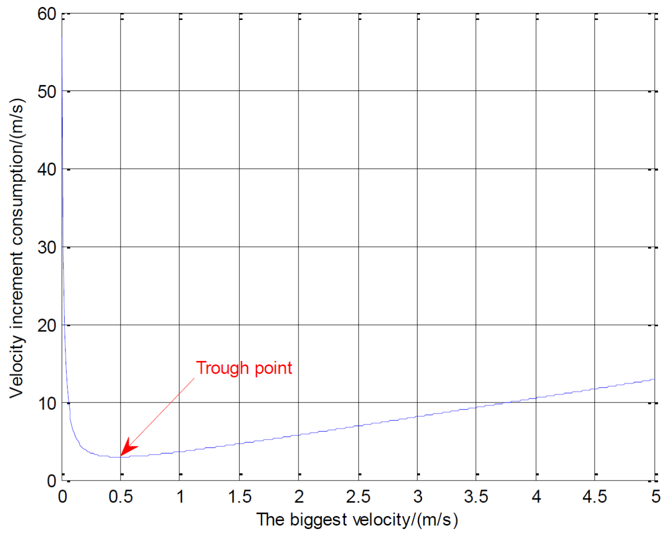

Figure 6: Fuel consumption with varying transfer speed for R-bar approach

5 Numerical simulations

In this section, the simulation results by using the proposed guidance methods are presented. To ensure the fairness of comparing these two methods, some basic settings are the same as follows.

The target is assumed to be orbiting a circular trajectory that the height is 260 km while the orbital inclination is 19 degrees. The initial mass of the chaser is 2000 kg while the biggest output thrust of propulsion in x-axis and z-axis direction is 10 N. Moreover, the thruster's specific impulse is 285 s and the fuel consumption is calculated as follows:

$$m_{\text{fuel}} \approx \frac{m_0 \Delta V_{total}}{I \cdot g_0} \tag{31}$$

where m_0 denotes the chaser's initial mass, I is the specific impulse, and $g_0 = 9.80665\,\text{m}/\text{s}^2$ is the gravitational acceleration.

5.1 Simulation results for V-bar approach

The initial and expected terminal conditions are shown in Tab. 1. According to Eq. (8) (alternatively Eq. (15)), the limitation of the minimum propellant consumption for V-bar approaching is $2n\Delta x = 0.4344$ kg.

Based on the above parameters, the simulation results for fixed-speed and varying-speed V-bar approaching algorithm presented in Section 3 are shown in Tab. 2. It can be seen that the total fuel consumptions of the proposed two scheme are almost the same. However, the transfer time for varying-speed approach scheme is much longer than that for fixed-speed scheme, i.e., 352% increment. Thus, the fuel consumption for V-bar case would not increase when the continuous low-thrust standing for impulse-thrust is used. As a result, it is more practical to use continuous low-thrust guidance when the requirement of transfer time is not so strict.

Table 1: Setting of initial and expected states for V-bar approach

	x(m)	y(m)	z(m)	v_x(m/s)	v_y(m/s)	v_z(m/s)
Initial state	-400.0	0.0	0.0	0.0	0.0	0.0
Expected state	-140.0	0.0	0.0	0.0	0.0	0.0

Table 2: Simulation results for V-bar approach

	Transfer time (s)	Transfer speed (m/s)	Total velocity increment (m/s)	Fuel consumption (kg)
Fixed-speed	121.4	2.142	4.8902	3.4994
Varying-speed	549.7246	2.1416 (average)	4.8902	3.4994

5.2 Simulation results for R-bar approach

The initial and expected terminal states for R-bar approach are shown in Tab. 3 while other parameters are the same as those for V-bar approach in Subsection 5.1. According to Eq. (22) and Eq. (30), the fuel-optimal results for fixed-speed and varying-speed approach scheme can be obtained respectively, as shown in Tab. 4. It can be seen that the fuel consumption of the varying-speed case is about 8% more than that of fixed-speed case, while the corresponding increment of transfer time is about 30%. Thus, as to the R-bar straight-line approach case, more transfer time means more fuel consumption. However, the more fuel consumption is not on the lifting of orbit altitude but on the forced motion to compensate the orbital drifting along x-axis and y-axis. As a result, a more fast approach with less fuel consumption would be achieved when pulse thruster is available, whilst more transfer time and fuel consumption would be cost under the case of continuous low-thrust.

Table 3: Setting of initial and expected states for R-bar approach

	x(m)	y(m)	z(m)	v_x(m/s)	v_y(m/s)	v_z(m/s)
Initial state	0.0	0.0	400.0	0.0	0.0	0.0
Expected state	0.0	0.0	140.0	0.0	0.0	0.0

Table 4: Simulation results for V-bar approach

	Transfer time (s)	Transfer speed (m/s)	Total velocity increment (m/s)	Fuel consumption (kg)
Fixed-speed	489.8959	0.5307	2.7299	1.9535
Varying-speed	636.5465	0.4812(average)	2.9486	2.1100

6 Conclusions

This paper presents an optimal-line guidance algorithm based on continuous low-thrust in the context of Clohessy-Wiltshire dynamics for the final translation phase of space rendezvous. Guidance schemes based on fixed-speed and varying-speed modes by using constant/finite low-thrust respectively are studied for V-bar and R-bar approach, and the optimal-fuel conditions are achieved. Detailed performance analysis for the proposed algorithm are conducted and presented based on numerical simulations. The results show that there is no obviously different between the two modes for V-bar approach in the aspect of fuel consumption, but more transfer time would be spent when finite low-thrust is used. Differently, more transfer time and more fuel consumption would be cost for R-bar approach when finite low-thrust used.

Further, the proposed methods are based on Clohessy-Wiltshire dynamics which is only suitable for near-circular orbit case. The optimal straight-line guidance scheme for elliptical orbit based on such as T-H equations would be solved in next work.

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