Orbital transport system - the concept and mechanics of orbital motion

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Abstract. A brief introduction to the meaning of on-orbit services and research on space-based services is provided in this work. In the context of on-orbit service, the near-circular orbit is idealized as a disturbed circular orbit, and a general equation for the optimal maneuver of the near-circle orbit is presented. The examples of coplanar on-orbit services in low, medium and high orbits are analyzed respectively, and the best maneuvering scheme for orbit transfer is solved by special software. Further analysis of the impact of different heights of parking orbit on the optimal maneuvering scheme reveals that the closer parking orbit to the target orbit, the less energy is required for maneuvering, but the phase-modulation time and the transport capacity of the launch vehicle should be considered comprehensively.

1. Introduction
Orbital systems, which belong to artificial space systems operating in space orbits, include orbital satellites, spacecraft, space shuttles, space stations (laboratories), space probes and telescopes, etc. Due to the limitations of the space system; the influence of the space environment; the absence of replenishment and maintenance, the orbital systems are often forced to lose efficacy. In addition, the failure of the old space system requires the launch of a new spacecraft for replacement. This leads to economic losses. Literature [1] first proposed the concept of clearing space debris. Russian scholars in the literature [2, 3] have established on-orbit service methods for dealing with space debris. In addition, NASA in the United States has also conducted systematic research on on-orbit services [4, 5]. On-orbit services are designed to extend the life of the orbital space system, expand and improve system performance, perform any space operations, such as inspection, calibration, maintenance, repair and updating of the system in orbit, as well as update the system for backup or emergency. The use of the system further facilitates the aerospace mission, reduces the life cycle cost of the system in orbit, improves overall performance, reduces risk and increases the flexibility of the space mission. The operating system consists of three parts: “Autonomous space transport and orbital robot” (service station), “service vehicle” (active device) and “serviced vehicle” (space vehicle - target). On-orbit service trajectory information as shown in Fig. 1.
In this paper, the on-orbit service is taken as the background for studying the transition and the possible meeting of active spacecraft and the spacecraft of the target in coplanar orbits. The space-based system of the on-orbit service is discussed, in the case of known the information of parking orbit and target orbit, the parameters of the transition orbit. Several maneuvering schemes are considered for meeting spacecraft, and the best maneuvering scheme is calculated when considering meeting time. The influence of different heights of parking orbit on the optimal transfer plan is discussed, and the parking orbits selection scheme for low, medium and high service orbits is analyzed separately.

2. Equation of orbital maneuvers
We introduce a coordinate system $Oxyz$, whose center is located in the center of gravity, the axis $Ox$ is directed to the point specified in the final orbit (see Fig. 2), the axis $Oy$ lies in the plane of the orbit.

The relationship between the deviations introduced above and the orbital elements is given by the following system of equations:
\[ \Delta a = 2(\Delta r + \frac{\Delta V}{\lambda_0}), \]

\[ e_x = \frac{\Delta r}{r_0} + 2 \frac{\Delta V}{V_0}, \] (1)

\[ e_y = -\frac{\Delta V}{V_0}, \]

where \( V_0, \lambda_0 \) – orbital and angular speeds of motion along the reference circular orbit of radius \( r_0 \) (\( r_0 = a_f \)); \( a \) – semi-major axis of the orbit; \( \Delta a \) – its difference from \( r_0 \); \( e_x, e_y \) – projections of eccentricity vector on axis \( x \) and \( y \). Eccentricity vector \( e \) is called a vector directed toward the pericenter of the orbit and have an eccentricity value \( e \).

For near-circular motion, the conditions for reaching a given point of a finite orbit can be written in the following dimensionless form [6-8]:

\[ \sum_{i=1}^{N} (\Delta V_i \sin \varphi_i + 2\Delta V_i \cos \varphi_i) = \Delta e_x, \]

\[ \sum_{i=1}^{N} (-\Delta V_i \cos \varphi_i + 2\Delta V_i \sin \varphi_i) = \Delta e_y, \]

\[ \sum_{i=1}^{N} 2\Delta V_i = \Delta a, \] (2)

\[ \sum_{i=1}^{N} (2\Delta V_i (1-\cos \varphi_i) + \Delta V_i (-3\varphi_i + 4\sin \varphi_i)) = \Delta t, \]

\[ \sum_{i=1}^{N} -\Delta V_i \sin \varphi_i = \Delta z, \]

\[ \sum_{i=1}^{N} \Delta V_i \cos \varphi_i = \Delta V_z, \]

Where: \( \Delta e_x = e_f \cos \omega_f - e_0 \cos \omega_0, \Delta e_y = e_f \sin \omega_f - e_0 \sin \omega_0, \Delta a = (a_f - a_0) / r_0, \Delta t = \lambda_0(t_f - t_0), \Delta z = z_0 / r_0, \Delta V_x = V_x / V_0, \Delta V_y = \Delta V_z / V_0, \Delta V_n = \Delta V_n / V_0, \Delta V_z = \Delta V_z / V_0. \)

It is necessary to clarify that this equation is a non-dimensional equation.

Here \( f_f, f_0 \) – indices corresponding to the final and initial orbits, \( e_f, e_0 \) – eccentricity of the orbit; \( a_f, a_0 \) – semi-major axes of the orbits; \( \omega_f, \omega_0 \) – angles between the direction to the pericenter of the corresponding orbit and the direction to the point specified in the final orbit (axis \( Ox \) – directed to this point); \( t_f \) – the required time of arrival at a given point, \( t_0 \) – initial maneuver time; \( z_0 \) – the deviation of the spacecraft in the initial orbit from the plane of the final orbit at the moment \( t_0; V_{z0} \) – lateral relative velocity at this moment; \( N \) – number of speed pulses; \( \varphi_i \) – the angle of application of the \( i \)-th velocity pulse, measured from the direction to a given point in the direction of the spacecraft; \( \Delta V_{n_i}, \Delta V_{r_i}, \Delta V_{z_i} \) – radial, transversal and lateral components of the \( i \)-th velocity pulse, respectively. It is necessary to take into account that the angles \( \varphi_i \) – negative because it was assumed that at a given point \( \varphi_f = 0 \).

2.1. Coplanar orbit transitions
2.1.1 Equations of motion of spacecraft for coplanar transitions

When calculating the parameters of transition maneuvers between coplanar orbits, lateral movement and time limit are not taken into account. Thus, the conditions for entering a given orbit (2), used (1) are:

\[ \sum_{i=1}^{N} (\Delta V_{ri} \sin \phi_i + 2\Delta V_y \cos \phi_i) = \Delta e_x \]
\[ \sum_{i=1}^{N} (-\Delta V_{ri} \cos \phi_i + 2\Delta V_y \sin \phi_i) = \Delta e_y \]  
\[ \sum_{i=1}^{N} 2\Delta V_{ri} = \Delta t \]  

The task of determining the parameters of optimal maneuvers [9-11] of transitions between coplanar orbits is formulated as follows: it is necessary to determine \( \Delta V_{ri} \), \( \Delta V_{ri} \), \( \phi_i \) \( (i = 1, ..., N) \), at which the total characteristic speed is minimal

\[ \Delta V = \sum_{i=1}^{N} \sqrt{\Delta V_{ri}^2 + \Delta V_{ri}^2} \]  

2.1.2 Types of coplanar transitions

Different types of orbits are shown in Fig. 3 – Fig.5, which can be classified as following three groups for coplanar orbits:

- Coplanar transitions between tangent orbits;
- Coplanar transitions between non-intersecting orbits (coplanar special solutions);
- Coplanar transitions between intersecting orbits (apsidal solutions).

![Transition between tangent orbits](image-url)
Fig. 4. Transition between non-intersecting orbits

Fig. 5. Transition between intersecting orbits

3. Calculation and analysis

3.1. Backup orbit for servicing low orbit

Taking the orbit of the International Space Station as the target orbit, the optimal maneuvering scheme is obtained according to equations (1) and (3), and the height of the parking orbit is changed to obtain the Table 1.

| Elements       | Initial orbit (0) | Final orbit (f) |
|----------------|-------------------|-----------------|
| \( H_{\text{min}} \) (km) | 180               | 401             |
| \( H_{\text{max}} \) (km) | 210               | 408             |
| \( \omega \) (deg) | 20                | 102.7           |

The calculation results are shown as follows:
\[
\begin{align*}
\varphi_1 &= 186,997^\circ \\
\varphi_2 &= 366,997^\circ \\
\Delta V_{r1} &= 65,0929 \text{ m/s} \\
\Delta V_{r2} &= 56,2913 \text{ m/s}
\end{align*}
\]

Table 2. Impact of changes in initial orbits on spacecraft maneuvers

| Initial orbit (0) \(H_{w_{\text{min}}} (km)\) and \(H_{w_{\text{max}}} (km)\) | Transverse velocity components, \(m/s\) | \(\Delta a\) |
|---|---|---|
| \(H_{w_{\text{min}}} = 180\), \(H_{w_{\text{max}}} = 210\) | \(\Delta V_{r1} = 65,0929 \text{ m/s}\), \(\Delta V_{r2} = 56,2913 \text{ m/s}\) | 0,0314 |
| \(H_{w_{\text{min}}} = 210\), \(H_{w_{\text{max}}} = 240\) | \(\Delta V_{r1} = 56,2025 \text{ m/s}\), \(\Delta V_{r2} = 47,4499 \text{ m/s}\) | 0,0268 |
| \(H_{w_{\text{min}}} = 240\), \(H_{w_{\text{max}}} = 270\) | \(\Delta V_{r1} = 47,3717 \text{ m/s}\), \(\Delta V_{r2} = 38,6675 \text{ m/s}\) | 0,0223 |
| \(H_{w_{\text{min}}} = 270\), \(H_{w_{\text{max}}} = 300\) | \(\Delta V_{r1} = 38,5999 \text{ m/s}\), \(\Delta V_{r2} = 29,9437 \text{ m/s}\) | 0,0178 |
| \(H_{w_{\text{min}}} = 300\), \(H_{w_{\text{max}}} = 330\) | \(\Delta V_{r1} = 29,8865 \text{ m/s}\), \(\Delta V_{r2} = 21,2779 \text{ m/s}\) | 0,0133 |
| \(H_{w_{\text{min}}} = 330\), \(H_{w_{\text{max}}} = 360\) | \(\Delta V_{r1} = 21,2313 \text{ m/s}\), \(\Delta V_{r2} = 12,6697 \text{ m/s}\) | 0,0088 |
| \(H_{w_{\text{min}}} = 360\), \(H_{w_{\text{max}}} = 390\) | \(\Delta V_{r1} = 12,6336 \text{ m/s}\), \(\Delta V_{r2} = 4,1186 \text{ m/s}\) | 0,0044 |

Fig. 6. Parameter \(\Delta a\) variation curve

From the variation \(\Delta a\) curve (see Fig. 6) and the Table 2, it can be seen that the higher the initial orbit, the less maneuvering of the active spacecraft occurs when moving in orbit. However, with an increase in the initial orbit, the phase adjustment time increases [12], therefore the height of the parking orbit...
should differ from the height of the orbit of the spacecraft — the target. We can choose an almost circular orbit, which is 50 ~ 100 km below the orbit of the spacecraft - the target.

### 3.2. Backup orbit for servicing medium-orbit spacecraft

Table 3 gives the information of the parking orbit and the target orbit, and calculates the speed maneuver required for the optimal transfer plan according to the method of 3.1. Change the height of the parking orbit to obtain Table 4. The best parking orbit height is also analyzed.

#### Table 3. Orbit parameters

| Elements     | Initial orbit (0) | Final orbit (f) |
|--------------|-------------------|-----------------|
| \( H_{\text{min}} \) \((km)\) | 10000             | 20000           |
| \( H_{\text{max}} \) \((km)\) | 10200             | 20200           |
| \( \omega \)(deg)    | 20                | 150             |

#### Table 4. Impact of changes in initial orbits on spacecraft maneuvers

| Initial orbit (0) | \( H_{\text{min}} \) \((km)\) and \( H_{\text{max}} \) \((km)\) | Transverse velocity components, \(m/\text{s}\) | \( \Delta a \) |
|-------------------|-------------------------------------------------|---------------------------------|----------------|
| \( H_{\text{min}} \) =10000 \( H_{\text{max}} \) =10200 | \( \Delta V_{11} = 511,3573 \text{ m/s} \) , \( \Delta V_{12} = 492,0142 \text{ m/s} \) | 0,465 7          |
| \( H_{\text{min}} \) =12000 \( H_{\text{max}} \) =12200 | \( \Delta V_{11} = 383,6593 \text{ m/s} \) , \( \Delta V_{12} = 366,0563 \text{ m/s} \) | 0,356 0          |
| \( H_{\text{min}} \) =14000 \( H_{\text{max}} \) =14200 | \( \Delta V_{11} = 271,4716 \text{ m/s} \) , \( \Delta V_{12} = 255,2657 \text{ m/s} \) | 0,255 6          |
| \( H_{\text{min}} \) =16000 \( H_{\text{max}} \) =16200 | \( \Delta V_{11} = 172,4568 \text{ m/s} \) , \( \Delta V_{12} = 157,3979 \text{ m/s} \) | 0,163 5          |
| \( H_{\text{min}} \) =18000 \( H_{\text{max}} \) =18200 | \( \Delta V_{11} = 84,7053 \text{ m/s} \) , \( \Delta V_{12} = 70,6053 \text{ m/s} \) | 0,078 5          |

![Fig. 7. Parameter \( \Delta a \) variation curve](image-url)
Since the parking orbit is closer (Fig. 7) to the target orbit, the energy consumption in the orbital transfer process is less. However, the height of the orbit depends on the carrying capacity of the launch vehicle. The higher the height of the parking orbit, the higher the requirements for the launch vehicle. Therefore, the choice of the height of the parking orbit should be considered comprehensively.

3.3. Backup orbit for servicing geosynchronous orbital service

Using the methods mentioned in 3.1 and 3.2, the optimal maneuvering scheme with geosynchronous orbit as the target orbit is calculated, and the influence of different parking orbital heights is discussed, as shown in Table 5.

### Table 5. Orbit parameters

| Elements | Initial orbit (0) | Final orbit (f) |
|----------|------------------|-----------------|
| $H_{\min} (km)$ | 10000 | 35786 |
| $H_{\max} (km)$ | 10200 | 36000 |
| $\omega (deg)$ | 20 | 150 |

### Table 6. Impact of changes in initial orbits on spacecraft maneuvers

| Initial orbit (0) $H_{\min} (km)$ and $H_{\max} (km)$ | Transverse velocity components, $m/s$ | $\Delta a$ |
|-------------------------------------------------------|--------------------------------------|-----------|
| $H_{\min} = 10000$, $H_{\max} = 10200$                | $\Delta V_1 = 816.2434$, $\Delta V_2 = 801.6189$ | 0.8783 |
| $H_{\min} = 12000$, $H_{\max} = 12200$                | $\Delta V_1 = 716.2677$, $\Delta V_2 = 703.0376$ | 0.7835 |
| $H_{\min} = 15000$, $H_{\max} = 15200$                | $\Delta V_1 = 582.7218$, $\Delta V_2 = 571.0910$ | 0.6525 |
| $H_{\min} = 20000$, $H_{\max} = 20200$                | $\Delta V_1 = 396.1379$, $\Delta V_2 = 386.3595$ | 0.4595 |
| $H_{\min} = 25000$, $H_{\max} = 25200$                | $\Delta V_1 = 244.9099$, $\Delta V_2 = 236.3912$ | 0.2928 |
| $H_{\min} = 30000$, $H_{\max} = 30200$                | $\Delta V_1 = 120.8623$, $\Delta V_2 = 113.2568$ | 0.1472 |
| $H_{\min} = 35000$, $H_{\max} = 35200$                | $\Delta V_1 = 18.0666$, $\Delta V_2 = 11.1546$ | 0.0189 |

As the Table 6 shows, a low-orbit maneuver consumes more power, so the parking orbit must be deployed as high as possible to meet the maintenance requirements. With an increase in the height of the parking orbit, the speed decreases sharply, and the rate of change is greatest within 12000 ~ 15000 km. If we simply consider the consumption of maneuvers, the higher the parking orbit, the better. However, given the power of the launch vehicle, the height of the initial orbit can be chosen equal to 12000 km.
4. Conclusion

This paper briefly introduces the concept and use of On-orbit service, and also examines the maneuvering of spacecraft in coplanar orbits. The general equation for the translation and of spacecraft is established. Several methods of coplanar orbital transition are introduced, and in the case of known information about the parking orbit and the target orbit, the optimal maneuvering scheme for the spacecraft transition is calculated.

Further, the effect of the height of the parking orbit on the optimal maneuvering scheme was studied. It was found that the closer the parking orbit to the target orbit, the less fuel consumed. The optimal heights of the parking orbit corresponding to low, medium and high orbits are discussed separately. In this paper, when discussing the height of the parking track for different target orbits, only the fuel consumption of the orbital transfer is considered. Planning a parking orbit to achieve one-to-one or one-to-more on-orbit service, the phase-modulation time and the carrying capacity of the launch vehicle should be considered. On-orbit services for non-coplanar are for further study.

5. References

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