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Inverse simulation system for evaluating handling qualities during rendezvous and docking

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ABSTRACT

The traditional method used for handling qualities assessment of manned space vehicles is too time-consuming to meet the requirements of an increasingly fast design process. In this study, a rendezvous and docking inverse simulation system to assess the handling qualities of spacecraft is proposed using a previously developed model-predictive-control architecture. By considering the fixed discrete force of the thrusters of the system, the inverse model is constructed using the least squares estimation method with a hyper-ellipsoidal restriction, the continuous control outputs of which are subsequently dispersed by pulse width modulation with sensitivity factors introduced. The inputs in every step are deemed constant parameters, and the method could be considered as a general method for solving nominal, redundant, and insufficient inverse problems. The rendezvous and docking inverse simulation is applied to a nine-degrees-of-freedom platform, and a novel handling qualities evaluation scheme is established according to the operation precision and astronauts' workload. Finally, different nominal trajectories are scored by the inverse simulation and an established evaluation scheme. The scores can offer theoretical guidance for astronaut training and more complex operation missions.

1. Introduction

Rendezvous and docking (RVD) refers to the event in which two spacecraft encounter each other at nearly the same velocity and dock together [1]. Due to the sophisticated and complex nature of a spacecraft, the automatic control system that manages RVD might face failures which, along with the uncertainty of the space environment, might lead to mission failure. A manual control system can act as a backup for the automatic control system and hence decreases the risk of mission failure. Though there is a trend to rely more on the automatic control system, the option of manual control is still required in manned space missions for proximity operations and docking [2].

Handling qualities are those characteristics of a flight vehicle that govern the ease and precision with which a pilot is able to perform a flying task [3]. In a man-in-loop system, handling qualities are used to characterise the control regulated by the human. Handling qualities evaluation is carried out using both analytical and experimental methods [4–6]. In the field of aeronautics, early systems were designed using analytical methods; subsequently, experimental methods were developed gradually. The former methods focus on pilot modelling: changing the pilot model parameters in the frequency domain to study the pilot's ability to compensate for the failures. McRuer et al. conducted early research on pilot modelling [7]. Neal and Smith summarised the results of former studies and proposed the well-known Neal–Smith model combined with a handling qualities rating scale for the frequency domain analysis of a human-in-the-loop system [8]. Kleinman, Baron, and Levison proposed an optimal control model [9], and Schmidt, Doman, and Anderson proposed further refinements to this model, resulting in increasingly accurate optimal control models [10,11]. Hess found a linear relationship between the objective function and handling qualities, according to which he predicted the flight vehicle handling qualities [12]. Thomson et al. employed an inverse simulation method to construct a helicopter simulation system that could perform initial handling qualities assessments [13,14].

In the field of astronautics, most studies on handling qualities tend to adopt experiment methods [15,16]. Designers utilise experimental platforms to simulate aerospace missions and record astronauts' sensations. To reduce the effects of individual differences and random factors, experiment designers train astronauts repeatedly and account for their cultural backgrounds, subjective positivity, and mental states. Because of these procedures, experimental methods are time-consuming, and the estimations from astronauts depend largely on subjective

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Abbreviations

DISS	Discrete inverse simulation system
MPC	Model predictive control
RVD	Rendezvous and docking

sensations, which cannot provide suggestions for improving operations. However, evaluation systems continue to use Aeronautical Design Standard rating scales such as the Cooper–Harper rating scale [17] and Task Load Index [18]. Therefore, an effective evaluation method for rating handling qualities when no operators participate in the initial design stage would be useful. The research reported in this document proposes to address this issue by developing an inverse simulation method for application to the RVD task that can reproduce astronauts' control strategies. By relating the simulation results to handling qualities metrics, the method can yield a quantitative evaluation of handling qualities that forms the basis of an assessment for initial system designs.

As the name implies, inverse simulation is a technique used to calculate the control action required to achieve a specified system response (such as pilot operations in the case of this study) [19]. Inverse simulation theory was first developed as a tool for aircraft dynamics analysis. Experimentally measured data or a mathematical representation can be used to simulate a particular mission, and a dynamic model of the system of interest used to compute the response and control strategies required to complete the mission. Inverse simulation has been referred to as 'desktop flight testing' [19]. The main applications of the theory include standard pilot modelling, aircraft model validation, handling qualities evaluation, and flight configuration studies. A differentiation method was first adopted to calculate the desired outputs [20,21]. Subsequently, Hess, Gao, and Wang proposed an integration method [22,23] to avoid the complexity and model restructuring required for the differentiation method, which was being widely used. The method was utilised by Thomson et al. to study helicopter manoeuvre performance and further develop the system for assessing handling qualities and planning breakdown operation schemes [24]. Later, the two-timescale method [25] and global optimization method [26] were proposed, both of which were based on the integration method. To decrease the computational cost, Avanzini, Thomson, and Torasso introduced a model-predictive-control architecture for the inverse simulation that improved the efficiency of the previous inverse simulation systems [27]. This architecture is the basis for the RVD inverse simulation system proposed in this paper. During the RVD manoeuvre, the motion states of the chaser spacecraft must be precisely controlled to guarantee that the target spacecraft remains in the sensor view. Control actions are executed by thrusters, which apply constant amplitude pulses. Therefore, in contrast to general inverse problems, the control signal of this system is discrete and the dimension of the motion states are larger than those of the control inputs.

This paper first proposes models for a spacecraft's relative orbit and attitude motion. The discrete inverse simulation (DIS) method is then constructed based on these models using a model-predictive-control architecture. Based on this system, which is verified by experimental data from a nine-degrees-of-freedom (9-DOF) RVD platform, and previous handling qualities rating scales, an improved assessment scheme is proposed to study the handling qualities of different mission configurations.

2. Inverse system modelling of RVD

2.1. Modelling of relative motion of spacecraft

The absolute dynamic equations between the target spacecraft and chase spacecraft without any hypothesis can be expressed as

$$\frac{d^2\boldsymbol{R}_{tar}}{dt^2} = -\frac{\mu\boldsymbol{R}_{tar}}{R_{tar}^3} + \boldsymbol{a}_{tar} \tag{1}$$

$$\frac{d^2\boldsymbol{R}_{cha}}{dt^2} = -\frac{\mu\boldsymbol{R}_{cha}}{R_{cha}^3} + \boldsymbol{a}_{cha} \tag{2}$$

where the subscripts *tar* and *cha* represent the target and chaser spacecraft, respectively; **a** is the acceleration caused by the external force, mainly the thrust of actuators here; R_{tar} and R_{cha} are the distance between the Earth's center and the target and chaser, respectively; μ and t are the standard gravitational parameter and time, respectively. The components of relative equations are given by

$$\begin{cases} \ddot{x} - 2\omega\dot{z} - \omega^2 x - \dot{\omega} z + \frac{\mu}{[(R_{tar}-z)^2+x^2+y^2]^{3/2}}x = a_{fx} \\ \ddot{y} + \frac{\mu}{[(R_{tar}-z)^2+x^2+y^2]^{3/2}}\dot{y} = a_{fy} \\ \ddot{z} + 2\omega\dot{x} - \omega^2 z + \dot{\omega} x + \frac{\mu}{R_{tar}^2} - \frac{\mu}{[(R_{tar}-z)^2+y^2+x^2]^{3/2}}(R_{tar}-z) = a_{fz} \end{cases} \tag{3}$$

where ω is the angular velocity, and a_{fx}, a_{fy}, and a_{fz} are the components of $\mathbf{a}_{\mathbf{cha}} - \mathbf{a}_{\mathbf{tar}}$ in the Hill coordinate system, respectively. The functions can be simplified by making the following acceptable assumptions [28]: the Earth is a homogeneous sphere; gravitational perturbation can be ignored; the orbit of the target is circular, and the distance between the target and chaser is much less than the target orbital radius. Therefore, the Hill coordinate system illustrated in Fig. 1 and Eq. (3) can be simplified as

$$\begin{cases} \ddot{x} - 2\omega\dot{z} = u_x \\ \ddot{y} + \omega^2 y = u_y \\ \ddot{z} + 2\omega\dot{x} - 3\omega^2 z = u_z \end{cases} \tag{4}$$

where u is the input control component in the Hill coordinate system. Eq. (4) can be further transformed into state equations.

$$\boldsymbol{x}(t) = \boldsymbol{\Phi}(t, t_0)\boldsymbol{x}(t_0) + \int_{t_0}^{t} \boldsymbol{\Phi}_{\boldsymbol{u}}(t, s)\boldsymbol{u}(\tau)ds \tag{5}$$

where $\mathbf{\Phi}(t, t_0)$ is the state transition matrix and $\mathbf{\Phi}_{\mathbf{u}}(t, t_0)$ is the input transition matrix. These matrices are expressed in Eq. (6) and Eq. (7), respectively:

$$\mathbf{\Phi}(t, t_0) = \begin{bmatrix} 1 & 6(s-\omega\Delta t) & 0 & (4s-3\omega\Delta t)/\omega & 2(1-c)/\omega & 0 \\ 0 & 4-3c & 0 & 2(1-c)/\omega & s/\omega & 0 \\ 0 & 0 & c & 0 & 0 & s/\omega \\ 0 & 6\omega(c-1) & 0 & 4c-3 & -2s & 0 \\ 0 & 3\omega s & 0 & 2s & c & 0 \\ 0 & 0 & -\omega s & 0 & 0 & c \end{bmatrix} \tag{6}$$

$$\mathbf{\Phi}_{\mathbf{u}}(t, t_0) = \begin{bmatrix} (4s-3\omega\Delta t)/\omega & 2(1-c)/\omega & 0 \\ 2(1-c)/\omega & s/\omega & 0 \\ 0 & 0 & s/\omega \\ 4c-3 & -2s & 0 \\ 2s & c & 0 \\ 0 & 0 & c \end{bmatrix} \tag{7}$$

where $\Delta t = t - t_0$, $s = \sin\omega\Delta t$, and $c = \cos\omega\Delta t$.

When the inputs are constant within a step, Eq. (5) can be expressed as

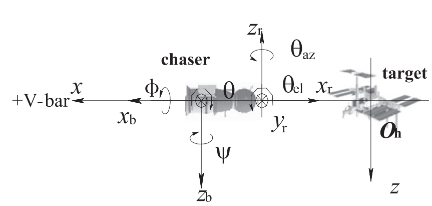

Fig. 1. Hill and body coordinate systems.