Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Failure effect analysis and reconfiguration of thrusters based on inverse simulation of manually controlled RVD

Wanmeng Zhou [a,*], Hua Wang [a], Douglas Thomson [b], Euan McGookin [b], Xiaohong Guo [c]

[a] College of Aerospace and Engineering, National University of Defense Technology, Changsha 410073, China
[b] School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK
[c] Xiaan Satellite Control Center of China, Xiaan 710000, China

A R T I C L E I N F O

Article history:
Received 19 December 2016
Received in revised form 18 October 2017
Accepted 13 March 2018
Available online xxxx

Keywords:
Manually controlled RVD
MPC structured inverse simulation
Failure mode and effect analysis
Risk classification
Reconfiguration

A B S T R A C T

Fault analysis of man-in-loop systems is a valuable issue worthy of being studied, especially in projects including high risk and high investment like manned space missions. Spacecraft sometimes must have the fault tolerance to complete their task even after errors occurring. Inverse simulation was previously proved to achieve manually rendezvous and docking (RVD) successfully. The aim of this paper is to demonstrate the potential applications of inverse simulation to undertake the thruster fault analysis and reconfigurations in manned RVD mission. Firstly, the inverse simulation system is established in a model predicted control structure. Then, the astronauts' operational strategy is analyzed through the thruster fault simulation, and an operational rate factor is proposed to assess the failure risk. In addition, the original configuration is transformed to strengthen the resistance under consideration of the fault tolerance. The comparative results indicate that the modified configuration can improve the performance effectively and then guarantee the success of the mission.

1. Introduction

The established manually controlled rendezvous and docking (RVD) system considered in this paper is composed of target spacecraft, chaser spacecraft, astronauts, sensor, and thrusters [1]. The orbit control and attitude control are completed by astronauts and controllers respectively. During the rendezvous process, astronauts can adjust positions and velocities of the chaser according to the relative information obtained from various sensors systems in order to achieve the final docking [2].

The modeling and analysis methods of man-in-loop dynamics system can be classified into the analytical method [3–6] and the experimental method [7–12]. Due to the safety concerns of astronauts, the fault experiment cannot be conducted in the real environment. Thus, the combined method of the experimental and analytical method is introduced to study the astronauts' operation under circumstances where there is a fault present.

Inverse Simulation (IS) is a technique to determine the required control inputs needed to achieve specified desired response, the aim of which is to calculate the required inputs of certain maneuvers, for example, the stick operation of the pilots [13]. Inverse simulation in the helicopter design stage is called "desk top flight test" [14], as it can simulate some specific testing flight and obtain the pilot's operations using models and some experimental data. This technique can be regarded as a method that combines experiment with analysis and is different from traditional simulation methods, in that it can acquire more flight information than open-loop or off-line design simulation methods [14,15]. In the previous research, an IS has been proved to reproduce the astronaut's operation successfully [16], while this paper aims at investigating the possibility of IS in analyzing the handling qualities in faulty conditions. After considering precision, efficiency, and stability of different algorithms [17–20], the model predictive control (MPC) [21] structured IS technique is chosen for the thruster fault simulation of the manually controlled RVD. Based on the simulation results, the operational strategy and the tolerance border of the system are studied and the thruster configuration is further designed.

Considerable research activities in Spacecraft design has been concerned with the configuration design of thrusters. As early as 1969, Crawford [22] proposed the linear programming method to design the time minimum and fuel minimum configurations. Then, Hwang et al. [23] designed the upper loaded stage using particle swarm optimization to gain the biggest achievement of control commands. Wang et al. [24] proposed an index representing for the limitation of control ability as a design factor for the thruster configuration. Moreover, there are some other investigations about

* Corresponding author.
E-mail address: zhouwanmeng13@nudt.edu.cn (W. Zhou).

https://doi.org/10.1016/j.ast.2018.03.019
1270-9638/

Please cite this article in press as: W. Zhou et al., Failure effect analysis and reconfiguration of thrusters based on inverse simulation of manually controlled RVD, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.03.019

Nomenclature

Symbol	Description	Unit
$\boldsymbol{a}_{cha}$	acceleration vector of chaser	m/s^2
$\boldsymbol{a}_{tar}$	acceleration vector of target	m/s^2
a_f	components of $\boldsymbol{a}_{cha}$–$\boldsymbol{a}_{tar}$ in Hill coordinate system	m/s^2
x, y, z	relative positions	m
R_{tar}	distance vector between the target and the earth center	m
μ	gravity constant	
ω_{tar}	angular velocity of the target orbit	rad/s
$\boldsymbol{\Phi}(t, t_0)$	state transforming matrix	
$\boldsymbol{\Phi}_u(t, t_0)$	input transforming matrix	
$\tau = \Delta t$	simulation time step t–t_0	s
$\boldsymbol{C}_{bh}$	transform matrix from body coordinate system to Hill coordinate system	
$\boldsymbol{C}_{tb}$	transform matrix from measurement coordinate system to body coordinate system	
θ_{az}	azimuth	rad
θ_{el}	elevation	rad
ϕ, ψ, θ	roll angle, yaw angle, pitch angle	rad
$\boldsymbol{I}$	rotational inertia matrix	$kg\,m^2$
$\boldsymbol{M}$	external moment vector	N m
$\boldsymbol{\omega}$	relative angular velocity vector	rad/s
x_t, y_t, z_t	target mass center coordinates in the measurement coordinate system	m
x_s, y_s, z_s	measurement center coordinates in the Hill coordinate system	m
ρ	slope distance of the target mass center	m
$\boldsymbol{p}$	vector from target mass center to chaser mass center	m
$\boldsymbol{p}_s$	sensor installing vector	m
$\boldsymbol{p}_t$	vector from the measurement center to the target mass center	m
$\lvert\theta_{az}\rvert_{\max}$	maximum azimuth angle	°
$\lvert\theta_{el}\rvert_{\max}$	maximum elevation angle	°
$\lvert\psi\rvert_{\max}, \lvert\theta\rvert_{\max}$	maximum attitude error	°
$\lvert y^*\rvert, \lvert z^*\rvert$	maximum offset	m
$\pm\dot{\theta}_s, \pm\dot{\theta}_l$	border parameters of the switching lines	rad/s
d, δ, a_0	switching line parameters	
btc_1, btc_2, btc_3	opening time parameters	
m	mass of the propellant	kg
$u_{\max}$	maximum thrust	m/s^2
u^*	outputs of the inverse simulation	m/s^2
$\hat{\boldsymbol{x}}(t)$	predicted state in one step	
$\hat{\boldsymbol{u}}$	inputs in one step (t–t_0)	m/s^2
$\Delta\tau$	opening time in one step τ	s
$n\Delta t$	n numbers of inverse simulation step	s
k_t, k_f	time sensitivity factor and acceleration sensitivity factor	
k	sensitivity factor of the system	
J	minimum cost function	
$\boldsymbol{Q}$	coefficient matrix reflecting the weighs of different components of states	
P_{thrust}	basic thruster amount	
k_p	operational pulse rate	

redundant online allocation [25–28] and coupling control with limited thrusters [29].

Configuration design not only includes the installing positions and orientations of thrusters but also the choice of the thruster type and control allocation strategy. The focus of this paper is the improvement of initial designed configuration in order to make RVD system resistant to the thruster faults. Wiktor [30] proposed the concept of minimum control authority and proved that the configuration is sufficient to the control mission when the amplitudes of the disturbing force and moment are in the limitation of the minimum control authority. However, there are some other cases when the mission is still controllable with the disturbance out of the limitation. In these cases, astronauts sometimes can still complete the mission by some specific compensations even though the disturbing force and moment caused by the fault thruster are beyond the minimum control authority. The manually controlled system has the characters of robustness, discreteness, nonlinearity, and uncertainty. Traditional methods using eigenvalues analysis and stability criterions are too complex for this system to determine the border of controllable disturbance. One effective way to solve this problem is to simulate directly to find the mechanism behind the mission failure. According to the IS results, the modified configuration can be proposed to improve the system resistance to the thruster fault.

This paper describes the application of IS to the analysis of thruster configuration through the following structure:

In the second section, the RVD model and attitude controller are established and then are integrated into RVD IS system; the third section introduces the original configuration and the fault modes of thrusters, and interprets the operation strategy and the physical workloads under both *single-axis* fault and *multi-axis* fault; in the fourth section, the modified configuration is proposed and verified according to fault simulation results; the last section concludes all the research findings of this paper.

2. Modeling of manually controlled RVD

2.1. RVD dynamics and kinematics modeling

The coordinate systems and parameters used in this paper are shown in Fig. 1.

$\boldsymbol{p}$ refers to the vector from target mass center to chaser mass center. $\boldsymbol{p}_s$ refers to the installing vector of the sensor. $\boldsymbol{p}_t$ refers to the vector from the measurement center to the target mass center. The Hill coordinate system is defined with z_h-axis orienting to the earth center, x_h-axis orienting to the velocity, and y_h-axis submitted to right hand regulation. All axes of body coordinate system are orienting to the body main axes. z_r-axis of measurement coordinate system is in the same direction of y_r-axis in body coordinate system. The directions of x_r-axis and y_r-axis are opposite to the directions of x_b-axis and z_b-axis, respectively. ϕ, θ, and ψ refer to the attitude parameters. θ_{az} and θ_{el} are the angles of the view.

Without any assumptions, the relative dynamics equations [2] are given by

$$\begin{cases} \ddot{x} - 2\omega_{tar}\dot{z} - \omega_{tar}^2 x - \dot{\omega}_{tar} z + \dfrac{\mu}{[(R_{tar}-z)^2 + x^2 + y^2]^{3/2}} x \\ \quad = a_{fx} \\ \ddot{y} + \dfrac{\mu}{[(R_{tar}-z)^2 + x^2 + y^2]^{3/2}} \dot{y} = a_{fy} \\ \ddot{z} + 2\omega_{tar}\dot{x} - \omega_{tar}^2 z + \dot{\omega}_{tar} x + \dfrac{\mu}{R_{tar}^2} \\ \quad - \dfrac{\mu}{[(R_{tar}-z)^2 + y^2 + x^2]^{3/2}} (R_{tar} - z) = a_{fz} \end{cases} \tag{1}$$

where a_f refers to the components of $\boldsymbol{a}_{cha}$–$\boldsymbol{a}_{tar}$ in the Hill coordinate system; x, y, and z refer to the relative positions; R_{tar} refers to the distance vector between the target and the earth center; μ is the gravity constant; ω_{tar} is the angular velocity of the target

Please cite this article in press as: W. Zhou et al., Failure effect analysis and reconfiguration of thrusters based on inverse simulation of manually controlled RVD, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.03.019