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Position Based Impedance Control on Space Docking

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In this paper, a Force Control Solution on Space Docking is proposed providing low impact and safe connection between space modules in different missions. In this solution, the force control concept has been employed along with traditional position control in space docking process because the interaction forces between those parties involved (the chaser spacecraft and the target) in this phase are quite significant. Among the available methods in the force control field, Position Based Impedance Control strategy has been used as this strategy controls neither position nor force but the dynamic relationship between relative positions and interaction forces which is used widely in robotic science; however, other methods exhibit instability problems at the connection stage due to change between the position controller and the force controller. As we know, there are different kinds of space vehicles with particular connection scenarios and various connection latches; in order that, each vehicle demands specific interaction force in the connection phase; therefore, Position Based Impedance Control combined with Hill's Equations, which is used for space docking in circular orbit as relative position, is presented to be applied to different docking strategies and mechanisms. For the position controller that lies into Position Based Impedance Control structure, a nonlinear-PID Controller has been utilized possessing an anti-windup property and good capability to track the reference signal. The results show that we can ensure low impact connection by modifying target impedance coefficients in addition to precise position control.

Keywords: *Force Control, Interaction Force, Position Based Impedance Control, Space Docking*

Introduction

In recent space missions, docking process is one of the most technological and critical stage of any mission such as: delivering and returning of the crew to/from space stations, repairing spacecraft in orbit and interplanetary missions. Rendezvous and docking mission are consisted of a series of crucial phases: launch, phasing, far range rendezvous and close-range rendezvous, and docking. During these phases, the kinematic and dynamic specifications, that will allow the parties to establish a connection, are continuously being controlled and modified. At the stage of docking and at the proximity of target spacecraft, it is essential to put the chaser spacecraft

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in slender boundaries of relative attitude, relative velocity and relative position, so it can establish a stable and safe connection [1, 2].

The chaser spacecraft must go through some elaborate operations such as different orbital maneuvers, rendezvous navigation sensors switches, and space-ground communication to reach the necessary conditions of docking process [3]. Ordinary directions of reaching the target point or keeping away from it are along the velocity vector in front of the target point or behind it, and radial, from above or below of the target, which is in the direction of the center mass of the Earth from the target point [4].

As the chaser spacecraft approaches the target spacecraft, it's necessary to decelerate according to the relative distance, and its relative velocity should decrease to a specific safe margin. Therefore thruster activity and control effort near the target (in docking operation) should be minimized to prevent plume impingement on the target vehicle and pollution of its surface, which is a challenging factor in reducing relative velocity [5].

The difficulty of docking phase is to achieve a soft connection with suitable relative velocity and minimize the shock of collision. Controlling the force created between the parties involved is one of the key parameters of controlling interactive activities. There are two different approaches in robotic sciences field towards controlling forces created in interaction activities: The first one is Hybrid Position-Force control in which the observation of connection between manipulator end-effector and the environment is the basis and the space of end-effector coordinates can be divided into a force subspace and a position subspace. In this strategy, notable control law switching and task planning is required throughout the implementation phase; furthermore, it is possible that various instability and robustness issues happen during the transition between constrained and unconstrained motions [6].

The second method is Impedance control which aims to control neither position nor force but their dynamic relation called Desired Target Impedance. Hogan stated that generalize nonlinear impedance that is consisted of stiffness, damping and inertial characteristics may model this relationship. Impedance control provides a unified structure that takes both constrained and unconstrained motion control problems into account and is preferred over hybrid position-force control [7].

Impedance control concentrates on the interaction port and depicts the required behavior in terms of mechanical parameters that are independent from the strategy that this behavior wants to achieve. Impedance control is developed by a single control law that corresponds with external forces against the hybrid control method that attempts to control the force and position in two different directions. Briefly, this control method requires a reduced amount of task planning, shows more resistance against uncertainty and distractions, and provides a steady shift between constrained and unconstrained motion [6, 7, 8].

Niwa and Suzuki researched on designing a control system for actuators that are used in connection systems and utilize an adaptive control approach to accommodate the actuator's interaction force with the docking target's different kinds of kinetic energy [9].

Hui and Shangying comprehensively studied the structure of control system compliant force in docking systems, methods, and the process of designing force controller by μ synthesis theory. Compliant force control is developed on the inner loop position control of 6-DoF parallel robot and they showed that the compliant force controller is more reliable in terms of robust stability and performance compared with classical force controller[10].

Zhang and Huang mainly focused on the impact problem and safe contact during docking process of flexible probes. They have developed the docking's dynamic model based on flexible probe through using Lagrange analytical approach which supplies a platform to examine the contact situation in flexible docking impact. The impact models created by connection in two directions (tangential and normal) are expressed in details. Also, the ground-based docking impact investigations had been done to validate the theoretical conclusions[11].

All studies mentioned above are inadequate as they comprehensively assess all situations and different space vehicles as a control solution in space docking and integration with space docking equations which has been integrated in this paper. The purpose of this paper is to do some researches on space docking strategies and emphasize on the importance of minimizing impact at the moment of connection establishment in different strategy to prevent any hazardous effects on parties involved; therefore, we tried to integrate force control with relative motion equations in circular orbit (Hill's equations) to reach

a solution that could be applied for different space vehicles in manned or unmanned missions.

DYNAMIC OF MOTION

Space Docking Process

Space docking phase will start in the remaining few hundred meters toward the target spacecraft and will be accomplished by establishing the physical connection of chaser and target. In this section of space mission, we should be quite careful about angular alignment, relative approach velocity, lateral and angular rates, lateral alignment, attitude precision, and particularly relative position. When the chaser is getting closer to the target through approach corridor, there will be some disturbances that deviate the chaser from its main trajectory; therefore the actual trajectory will differ from the desired trajectory as shown in **Error! Reference source not found.** and this is one of the challenges of this phase.

There are two directions which are named V-bar (in direction of target spacecraft velocity) and R-bar (Along the line between the center mass of the Earth and the center mas of the chaser toward the earth) to reach the desired point; consequently, the Chaser spacecraft can use several strategies as shown in **Error! Reference source not found.** to move through these two directions.

For approaching to the target spacecraft from R-bar, the first way (trajectory c) is a fly-around maneuver which starts from a location on V-bar. Operational flexibility as a result of the feasibility of infinite staying time at V-bar due to relative velocity of zero in the same orbit is the superiority of starting from a position on V-bar that is called Hold Point. Another way

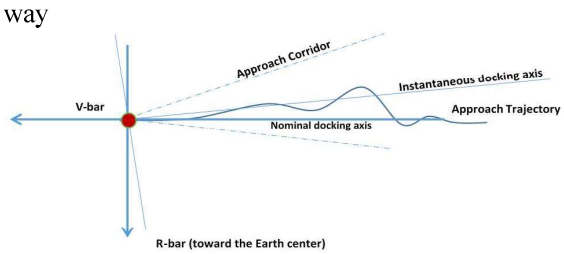

Fig. 1- Nominal and Actual Axis of Approaching corridor

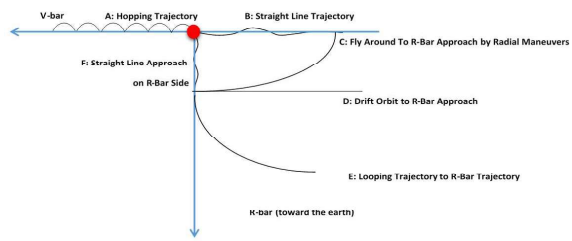

Fig. 2- Docking Strategies

To acquire a starting point on R-bar path (trajectory e) is a direct manner from an orbit in lower altitude rather than the target orbit through using radial impulse at the end of transfer path that leads to the natural upward movement.

Short duration of approaching and fuel-saving are the benefits of this strategy as intermediate routes have been deleted; nonetheless, there are some disadvantages in this strategy such as less safety aspects and inflexibility of time.

The last possible strategy is drifting to the approach corridor on R-bar in orbit with little lower altitude than the target orbit with the advantages of collision safety feature and propellant-saving. The specific amount of flexibility in time can be obtained by choosing different altitudes for the target orbit and chaser orbit [1].

Relative Motion Equation in the Target Reference Frame

The relative motion between the target and the chaser at the final stage is usually described in the local vertical local horizontal (LVLH) coordinate system which is shown in Fig. 1 [12].

The LVLH coordinate system is attached to the target and moves with it, the orbit of the target is assumed to be approximately circular and the distance between target and

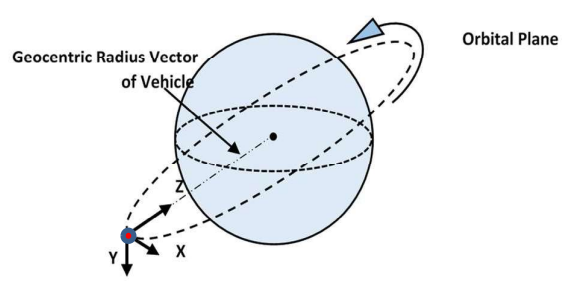

Fig. 1- LVLH Coordinate System

chaser is much smaller than the orbital radius, then the motion of the chaser relative to the target, can be expressed by Hill's equations[1, 13-16]:

$$\ddot{x} - 2w\dot{z} = F_x/m_c \quad (1)$$

$$\ddot{y} + w^2 y = F_y/m_c \quad (2)$$

$$\ddot{z} + 2w\dot{x} - 3w^2 z = F_z/m_c \quad (3)$$

In which $w = \frac{2\pi}{T}$ is the angular frequency of the target's orbit, m_c is the mass of chaser, and $F_{x,y,z}$ is chaser thruster or control effort. As shown above, motion in direction of x and z are coupled because the docking process occurs in the orbital plane and y direction will improve through orbital maneuvers. As the impact and docking are caused by translational moving, relative attitude is not included in this paper [1, 3].

FORCE CONTROL ON SPACE DOCKING

Impedance control

This method is a solution to control robot's interaction and fulfillment of its primary traditional task of position control whereas giving it the ability to manage static and dynamic interaction between robots and their environments. Impedance control makes a desired dynamic relation (called target's impedance) between robot's end effector position x and contact force f which imputed us to use this method on space docking. Hogan (1985) has shown that the desired impedance can be expressed as system of mass, spring and damper and this relationship can be formulated into the following three quadratic equations [6, 7, 8]:

$$M\ddot{x} + C\dot{x} + K(x - x_r) = e_f \quad (4)$$

$$M\ddot{x} + C(\dot{x} - \dot{x}_r) + K(x - x_r) = e_f \quad (5)$$

$$M(\ddot{x} - \ddot{x}_r) + C(\dot{x} - \dot{x}_r) + K(x - x_r) = e_f \quad (6)$$

In which, the term $(x - x_r)$ shows the deviation from the reference state x_r and parameters M, C, and K are respectively mass, damper, and stiffness of target impedance specified by user. The third formulation of desired target impedance that is used in this paper is illustrated in Fig. 2.

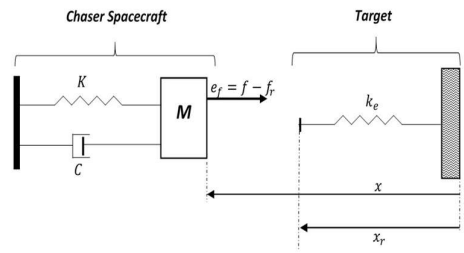

Fig. 2. Physical interpretation of Target Impedance model

There are two forms of impedance control: Torque-Based Impedance Control (TBIC) and Position-Based Impedance Control (PBIC). In torque-based impedance control a force/torque controller is required inside the inner loop and actual position modifies the necessary force/torque to attain the desired impedance. Against that, in position-based impedance control the inner loop contains position controller, and the measured interaction force modifies the required position to attain the desired target impedance in which the desired interaction force has been considered.

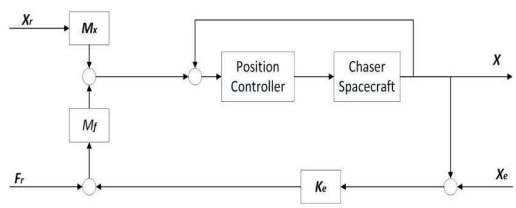

Fig. 5. Position Based Impedance Control Block Diagram

Block diagram of position-based impedance control is as **Error! Reference source not found.** in which x_r and f_r are reference points of position and interaction force, the gains M_x and M_f are second order transfer functions that respectively influence the reference of position and error of the force used for acquisition of desired position x_d [8].

Target's docking window is modeled by a linear spring with the stiffness of K_e and location of X_r. With respect to Fig. 2 and **Error! Reference source not found.** the force that is applied on target and its feedback get into block diagram to modify the position in free-space motion or contact situation, by considering the coordinate system that is attached to target spacecraft, can be expressed as below:

$$F_e = \begin{cases} K_e(X - X_r) & X \le X_r \\ 0 & X > X_r \end{cases} \quad (7)$$

That means during the free-space motion in which there is

no contact with target, $F_e = 0$ and the position controller works solely. With respect to **Error! Reference source not found.** the modified position that enters into the controller is as below[18]:

$$X = M_x X_r + M_f (F_r - F_e) \quad (8)$$

And the gains M_x and M_F as transfer functions to form the desired Cartesian position from the third formula (Eq. 6) can be obtained as below:

$$Ms^2(X - X_r) + Cs(X - X_r) + K(X - X_r) = e_f \quad (9)$$

Then by sorting and dividing two side of equation to" $MS^2 + CS + K$", we'll have

$$X = \left(\frac{Ms^2 + Cs + k}{Ms^2 + Cs + k}\right) X_r + \left(\frac{1}{Ms^2 + Cs + k}\right) e_f \quad (10)$$

Which by comparison with equation 8, the modification coefficients for the third formula are as below:

$$M_F = \frac{1}{Ms^2 + Cs + K} \quad (11)$$

$$M_x = \frac{Ms^2 + Cs + K}{Ms^2 + Cs + K} = 1 \quad (12)$$

In a same way, the modification coefficients for the second formula (Eq. 5) are as below:

$$M_F = \frac{1}{Ms^2 + Cs + K} \quad (13)$$

$$M_x = \frac{Cs + K}{Ms^2 + Cs + K} \quad (14)$$

and for the first formula of Impedance Equation (Eq. 4), the modification coefficients are as below [6, 8]:

$$M_F = \frac{1}{Ms^2 + Cs + K} \quad (15)$$

$$M_x = \frac{K}{Ms^2 + Cs + K} \quad (16)$$

PBIC technique requires a position controller that performs well at both regulation and tracking with different inputs which is the goal of next part. Also, in **Error! Reference source not found.** implementation of Hill's Equation in structure of PBIC is shown which is related to space docking in circular orbit and relative position of the chaser and target spacecraft.

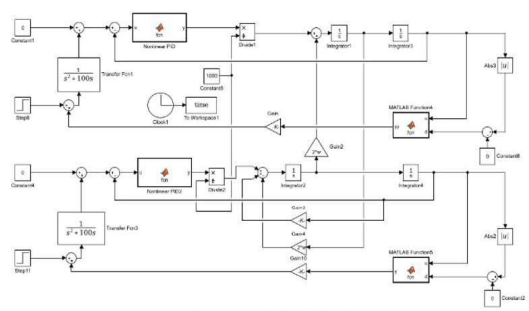

Fig. 6- Implementation of Hill's Equations in in PBIC Structure by Simulink

DEVELOPMENT OF CONTROLLER FOR PBIC

To have a better controller performance inside PBIC, a PD-nonlinear integral controller has been applied that is invented by Morse and differs from normal PID controller since it computes the integral error as shown below:

$$I(t) = (I(t - \Delta t) + e(t)\Delta t)\left(\frac{\alpha}{\alpha + \dot{p}^2(t)}\right) \quad (17)$$

So that t is the time and Δt is the time interval, $\propto$ is an arbitrary constant controller gain, p is the controlled position and $e(t) = p_d(t) - p(t)$ is the error in the position in which p_d is desired position. The nonlinear multiplier (rate varying) is equal to zero at high velocity and as high as unity at low velocity. This form of nonlinearity in integral parts is established to overcome overshoot and decrease the influence of stiction as it aims to reduce the impact of integral part at high speeds by resetting itself. This kind of nonlinearity in integral part of the controller is known as Morse's method in control literature[19].

This strategy conforms well to step change and allows using higher integral gains and control action at low speed. Nevertheless, as high speed tracking in space missions is ideal, therefore the following change was applied to nonlinear multiplier of integral calculation to improve the performance of tracking situation [8]:

$$I(t) = (I(t - \Delta t) + e(t)\Delta t)\left(\frac{\alpha}{\alpha + \dot{e}^2(t)}\right) \quad (18)$$

Using $\dot{e}(t) = \dot{p_d}(t) - \dot{p}(t)$, the velocity error, in the nonlinear multiplier rather than the velocity itself has two advantages. The first one is that the integral part will only reset in positions where integral windup is a probability, i.e. when the set-point is shifting rapidly. The second advantage of the modified method is being identical to the original method meant for a step change in the set-point.

However, the disadvantage of this qualification is that anti-stiction feature of the original Morse controller is a little decreased which is not an important factor.

CASE STUDY AND RESULTS

In this paper, in addition to traditional position control, we care about the interaction forces between chaser and target spacecraft so we used PBIC solution. It is assumed that the orbit for docking procedure is circular which permits us to use Hill's relative motion equation in space docking. As preferred to have a low impact connection in every space docking mission, therefore, the interaction force references (F_r) in each direction will be considered equal to zero (Also it is possible to apply this method to have specific Non-Zero interaction force between parties for different purposes).
We applied different values of mass (M), damping (c), and stiffness (K) in desired target impedance related to PBIC to understand their effects on interaction forces and through modifying these values, we tried to minimize the interaction forces. Initial conditions and target position are mentioned in Table 1.

Table 1. Initial conditions

Parameter	value
Initial position of chaser (m)	[10,10]
Target position (m)	[0,0]
Mass of chaser (Kg)	1000
Orbit Characteristics	Circular (ISS orbit)

In **Error! Reference source not found.** the effect of change in each coefficient of desired target impedance on interaction force is shown and it says that high values of target impedance coefficients will lead to higher amount of interaction force and it needs more time to compensate this force. For example the left column of **Error! Reference source not found.** relates to effect of M coefficient in which by reducing the value of M coefficient, value of interaction force decreased from 120 N to 20N and the time that is needed to compensate this force reduced from about three seconds to one second. By changing values of transfer functions (target impedance), we see that the optimal condition with M=0.1(kg), C=50(Ns/m), K=1(kg m/s^2) with minimum interaction forces and impact have been obtained. Results for position control and interaction forces are shown in **Error! Reference source not found.** and it indicates that relative position is suitably controlled and interaction forces that are created at the moment of contact compensate after modifying the position which is the aim of PBIC to adapt required position based on measured interaction forces.

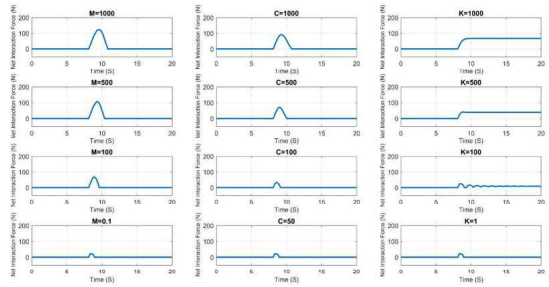

Fig. 7. Effect of change in Target Impedance's Coefficients on Net Interaction Force (M (kg), C (N.s/m), K (Kg.m/s^2)

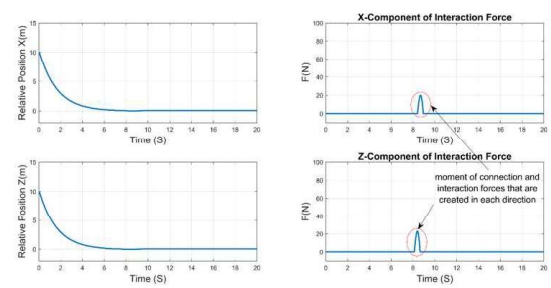

Fig. 8. PBIC on Space Docking with target impedance M=0.1(kg), C=50(N s/m), K=0(kg m/s^2)

Also, relative velocity of chaser from relative hold point is shown in **Error! Reference source not found.** that tends to zero before connection and has a little correction at the moment of connection to compensate extra interaction forces.

CONCLUSION

It's important to have the lowest interaction forces in space docking to avoid damage to the structures and crews in both chaser and target spacecraft. As there are different space vehicles with different strategies to dock a target with different interaction forces that are needed to activate interaction latches and also to prevent increase in interaction forces between parties in any space docking mission, we decided to involve force control in space docking. Position Based Impedance Control is a solution to control the forces in interaction activities of robotic science which we applied on space docking in this paper. Theoretical results showed that measured interaction forces modified the required position to reach a desired values and it is possible to decrease interaction forces by changing target impedance

coefficients. For the future, we suggest studies that can enhance the ability of PBIC for force tracking and use artificial intelligence to find optimal target impedance coefficients (M, C and K) to have the lowest impact on space docking and minimize interaction forces.

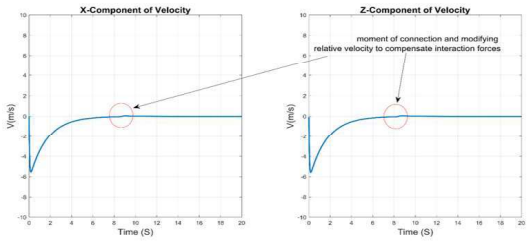

Fig. 9- Chaser Velocity

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