Full Length Article

An optimal fuzzy PID control approach for docking maneuver of two spacecraft: Orientational motion

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A B S T R A C T

This paper describes a scheme for a Fuzzy-Proportional Integral Derivative (FPID) controller based on genetic algorithm (GA), in a docking maneuver of two spacecraft. The docking maneuver consists of two parts: translation and orientation. Euler’s gyroscopic equation is applied to obtain governing equations of orientational phase. Here, a designed fuzzy-PID controller for stabilization purpose of orientational phase of a docking maneuver is presented based on the Single Input Fuzzy Inference Motor (SIFIMs) dynamically connected Preferrer Fuzzy Inference Motor (PFIM). This fuzzy-PID controller takes the error signal of Euler’s angles and the error of angular velocities of the chaser as its input items, and the driving force as its output. The parameters of the controller are ascertained by using a genetic algorithm. Conflicting objective functions (which their 3D pareto frontiers are obtained by Multi-objective Genetic Algorithm (MOGA)) are distance errors from the set point, angle errors from the set point, and control efforts. Optimization constraint is maximal of the momentum produced by momentum wheels. The result of optimum point demonstrates that the designed controller makes an efficient performance in the orientational phase of the chaser spacecraft. Compared to similar works, some of system parameters like settling time are improved and overshoot (as a critical parameter in docking maneuver) is decreased.

1. Introduction

The rendezvous and docking (RVD) process consists of a series of orbital maneuvers and controlled trajectories, which eventually dock the chaser with the target. The term docking is used for the case where the Guidance, Navigation and Control (GNC) system of the chaser controls vehicle state parameters to ensure entering its capturing interfaces into those of the target vehicle, and the capture location is the location for structural connection [1]. For an actively-maneuvering spacecraft, a docking mechanism is used for joining to other spacecraft to constitute an integral unit. Recovering a tumbling satellite, Capturing the target satellite and controlling re-entry into atmosphere, performing repair, in-orbit servicing of low Earth orbit satellites, multiple docking of spacecraft capsules for extending the mission objectives, makes the docking maneuver a necessity in space missions [1–3].慕容

Docking task has a wider domain of applications than that pertaining to space. Docking plays an important role for any mobile robot, looks for interaction with objects [4,5]. Various control strategies have been applied to Autonomous Underwater Vehicle (AUV) docking task. [6–8]. Villagra and Herrero-Pérez [9] presented a comparison in detail between different control approaches for Automated Guided Vehicle (AGV) robust path tracking.


Fuzzy systems are knowledge-based or rule-based systems formed via human knowledge and heuristics. They have been applied to a wide range of fields such as control, communication,
The development of fuzzy-PID controllers for various engineering problems has been a major research activity in recent years. Different kinds of studies have been done in applying fuzzy logic to docking maneuver problems. A guidance control method based on fuzzy logic system is proposed for the mission of autonomous rendezvous and docking with non-cooperative target spacecraft [25]. Leitner et al. [26] designed a neurocontroller to reproduce the optimal control for an automatic rendezvous and docking task.

The heuristic parameters of fuzzy-PID controllers have to be determined via an appropriate approach. A very effective way to choose these factors is the use of evolutionary algorithms, such as genetic algorithm (GA). A constrained optimization of a simple fuzzy-PID system is designed for the online improvement of PID control performance during productive control runs [27]. Duan et al. [28] proposed an inherent saturation of the fuzzy-PID controller revealed due to the finite fuzzy rules. Oh et al. [29] developed a design methodology for a fuzzy PD cascade controller for a ball-beam system using particle swarm optimization (PSO). An on-line tuning method is proposed for fuzzy PID controllers via rule weighing [30]. Boubertakh et al. [31] proposed a new automatic tuning fuzzy PD and PI controllers using reinforcement-learning (QL) algorithm for SISO (single-input single-output) and TITO (two-input two-output) systems. Nie and Tan [32] presented an improved version of the stable fuzzy adaptive control structure.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{xx}$</td>
<td>2000</td>
<td>Chaser angular mass around $x$ [kg/m²]</td>
</tr>
<tr>
<td>$J_{yy}$</td>
<td>5000</td>
<td>Chaser angular mass around $y$ [kg/m²]</td>
</tr>
<tr>
<td>$J_{zz}$</td>
<td>2000</td>
<td>Chaser angular mass around $z$ [kg/m²]</td>
</tr>
</tbody>
</table>

![Fig. 1. Schematic of designed controller structure.](image1)

![Fig. 2. RVD mission elements breakdown.](image2)

![Fig. 3. Chaser and target spacecraft: before and after orientation phase.](image3)
which comprises an approximation of the ideal controller and a supervisory controller. Mahmoodabadi and Jahanshahi [33] studied multi-objective optimization algorithms for the optimum design of the fuzzy PID controller for two nonlinear benchmarks.

Fig. 4. The block diagram of the optimal fuzzy-PID control.

Table 2
The membership functions of SIFIM for the spacecraft system.

<table>
<thead>
<tr>
<th>If</th>
<th>Then</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_i \leq -1$</td>
<td>$V_B = -1$</td>
</tr>
<tr>
<td>$-1 &lt; X_i \leq 0$</td>
<td>$P_O = 0$ $Z_B = 0$</td>
</tr>
<tr>
<td>$0 &lt; X_i \leq 1$</td>
<td>$V_B = -X_i$ $P_O = -X_i + 1$ $Z_B = 0$</td>
</tr>
<tr>
<td>$1 \leq X_i$</td>
<td>$V_B = 0$ $P_O = 0$ $Z_B = X_i$</td>
</tr>
</tbody>
</table>

Fig. 5. Membership functions for each SIFIM.

Table 3
The rules of SIFIMs for the spacecraft system.

<table>
<thead>
<tr>
<th>If</th>
<th>Then</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_i (i = 1, 2, 3, 4, 5, 6, 7, 8, 9)$</td>
<td>$f_{11} = -1$ $f_{12} = 0$ $f_{13} = -1$</td>
</tr>
</tbody>
</table>

Table 4
The membership functions of PFIM for the spacecraft system.

<table>
<thead>
<tr>
<th>If</th>
<th>Then</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>X_i</td>
</tr>
<tr>
<td>$0.5 &lt;</td>
<td>X_i</td>
</tr>
<tr>
<td>$</td>
<td>X_i</td>
</tr>
<tr>
<td>$0.5 &lt;</td>
<td>X_i</td>
</tr>
<tr>
<td>$</td>
<td>X_i</td>
</tr>
<tr>
<td>$0.5 &lt;</td>
<td>X_i</td>
</tr>
</tbody>
</table>
In their work an integral term was augmented to the state variables in order to eliminate the steady state errors and decrease the rising time. Sahib [34] proposed an optimized proportional, integral, derivative and second order derivative order (PIDD$^2$) using particle swarm optimization for automatic voltage regulator (AVR). Ortega and Giron-Sierra [35] studied the use of Genetic Algorithms (GAs) to perform the optimization of the fuzzy controller by finding the best fuzzy sets of the membership functions, to optimize docking time and fuel consumption.

In this paper, the novel optimal Fuzzy-PID control strategy for orientational part of a docking maneuver of two spacecraft is proposed. To derive governing equations for orientational phase of docking, Euler’s gyroscopic equation is used which then transformed to state space form. Here, SIFIMs dynamically connected PFIM are utilized as two fuzzy inference motors. The parameters of the controller are ascertained by using a genetic algorithm. 3D Pareto-frontiers of conflicting objective functions (which obtained by MOGA) are distance errors from the set point, angle errors from the set point, and control efforts. Optimization constraint is maximal of the momentum produced by momentum wheels. The result of optimum point demonstrates that the designed controller makes an efficient performance in the costs of orientational phase of the chaser spacecraft and could satisfy the mission time. Finally, compared to similar works, priority of our work in some of system performance parameters (e.g. settling time and overshoot) are discussed.

2. Optimal fuzzy-PID controller design

In this section, the optimal fuzzy-PID controller is designed for the chaser spacecraft. For orientational motion of chaser and target spacecraft, fuzzy-PID controller would be implemented. Fig. 1 demonstrates a schematic view of designed controller structure in this work. As it shown, outputs are compared with their desired input values and error function which is the input of fuzzy and PID controllers is made. Base and regulation variables obtained by genetic algorithm in $θ−φ−ψ$ directions and the error function, are considered as fuzzy controller inputs. Fuzzy controller calculates integral-proportional-derivative coefficients of PID controller and with multiplying these values by integral-proportional-derivative of input error by PID controller, final control force is made.

2.1. Orientation

At first step, the desired mission and required systems is mentioned, then dynamics of space vehicles for successfully accomplishing of noticed mission is studied. RVD mission can break

<table>
<thead>
<tr>
<th>If</th>
<th>Then</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>HS</td>
</tr>
<tr>
<td>$X_2$</td>
<td>HM</td>
</tr>
<tr>
<td>$X_3$</td>
<td>HB</td>
</tr>
<tr>
<td>$X_4$</td>
<td>HS</td>
</tr>
<tr>
<td>$X_5$</td>
<td>HM</td>
</tr>
<tr>
<td>$X_6$</td>
<td>HB</td>
</tr>
<tr>
<td>$X_7$</td>
<td>HS</td>
</tr>
<tr>
<td>$X_8$</td>
<td>HM</td>
</tr>
<tr>
<td>$X_9$</td>
<td>HB</td>
</tr>
</tbody>
</table>

Table 5

The rules of PFIM for the spacecraft system.

Fig. 6. Membership functions for each PFIM.

Fig. 7. 3-D pareto front by objectives 1, 2, and 3 of optimal fuzzy-PID for orientational phase of chaser spacecraft.

down into several components and sub-components. Rendezvous operation providing conditions for docking task, splits up into the two parts:

- **Far range Rendezvous** operation whose main purpose is reduction of trajectory dispersions and achievement of proper position, velocity and angular rate conditions for initiation of close range rendezvous operation. Suitable navigation during rendezvous (i.e. far range or close range rendezvous) is achieved based on direction and range relative measurements or directly by relative position.
- **Close range rendezvous** is usually divided into two subphases: a preliminary phase providing conditions for closing and a final one which leads to the mating. In the closing phase, reduction

**Fig. 8.** 3-D pareto front by objectives 1, 2, and 4 of optimal fuzzy-PID for orientational phase of chaser spacecraft.

**Fig. 9.** 3-D pareto front by objectives 1, 2, and 5 of optimal fuzzy-PID for orientational phase of chaser spacecraft.
Fig. 10. 3-D pareto front by objectives 1, 2, and 5 of optimal fuzzy-PID for orientational phase of chaser spacecraft.

Fig. 11. 3-D pareto front by objectives 2, 3, and 4 of optimal fuzzy-PID for orientational phase of chaser spacecraft.
Fig. 12. 3-D pareto front by objectives 2, 3, and 5 of optimal fuzzy-PID for orientational phase of chaser spacecraft.

Fig. 13. 3-D pareto front by objectives 2, 3, and 6 of optimal fuzzy-PID for orientational phase of chaser spacecraft.
of range to the target and placing the chaser in suitable place for accomplishing the final phase of mission, is considered. The main purpose of final approach is acquiring proper berthing or docking conditions.

At the end of final approach phase, docking operation begins. Mating phase starts when the chaser GNC system, has delivered the capture interfaces of the chaser into the right range to the target. Capturing target by chaser is the final phase of RVD operation. Fig. 2 shows the RVD operation from launch to capturing phase.

Fig. 14. 3-D pareto front by objectives 3, 4, and 5 of optimal fuzzy-PID for orientational phase of chaser spacecraft.

Fig. 15. 3-D pareto front by objectives 3, 4, and 6 of optimal fuzzy-PID for orientational phase of chaser spacecraft.
By the end of rendezvous operation, two spacecraft stand in a position like Fig. 3a. Docking operation consists of two phases including orientation and translation. Firstly, chaser spacecraft should perform a rotational motion to place its port along with the port of target spacecraft. At the end of orientation phase, two spacecraft are sit in the position as Fig. 3b. After this operation, only a translation phase is required for the final docking.

Now, the orientation equation of chaser is considered. Representing the inertia tensor with \( J \), Euler’s gyroscopic equation becomes as Eq. (1):

\[
j \cdot \omega + J \cdot \dot{\omega} + J \times (j \cdot \omega) = m
\]

(1)

There are two important assumptions taken: constant mass distribution over time, i.e., \( \dot{J} = 0 \) and the coincidence of system with the principal axes of the body \( \{j_k \neq 0 \} \). The state vector is the system observable state vector \( x = [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9] = [\theta, \theta, \omega_x, \omega_y, \omega_z, \dot{\theta}, \dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z] \). The state variables \( x_2, x_3, \) and \( x_6 \) denote Euler xyz-angles \( (\theta, \phi, \psi) \) respectively. The state variables \( x_1, x_4, \) and \( x_5 \) are integrals of the state variables \( x_2, x_3, \) and \( x_6 \), respectively. The additional state variables \( x_7, x_8, \) and \( x_9 \) are the respective angular velocities transforming the system into the nine first order differential Eq. (2):

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= \frac{1}{J_{yy}} \left( J_{yy} x_6 \left( f_{yy} - f_{zz} \right) + m_x \right) \\
\dot{x}_4 &= x_5 \\
\dot{x}_5 &= x_6 \\
\dot{x}_6 &= \frac{1}{J_{zz}} \left( J_{zz} x_6 \left( f_{zz} - f_{xx} \right) + m_y \right) \\
\dot{x}_7 &= x_8 \\
\dot{x}_8 &= x_9 \\
\dot{x}_9 &= \frac{1}{J_{xx}} \left( J_{xx} x_6 \left( f_{xx} - f_{yy} \right) + m_z \right)
\end{align*}
\]

where \( m = [m_x, m_y, m_z]^T \) describes the momentum vector.

The initial and desired values are \( x = [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9] = [0, 0, 0, 0, 0, -3.0023 \cdot 10^3, 0, 0, 0], \) \( x = [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9] = [0, 0, 0, 0, 0, 0, 0, 0, 0], \) respectively. The chaser angular mass around \( x, y, \) and \( z \) axes are listed in Table 1.

As shown in Fig. 4 the block diagram of the optimal Fuzzy-PID control (for stabilization control of orientation of the chaser spacecraft system) represents each of state variables \( f \theta, \theta, \omega_x, \omega_y, \omega_z, \dot{\theta}, \dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z \) relevant to the orientation of the chaser spacecraft system is fed back and compared with its desired value.

Two fuzzy inference motors are utilized in the suggested Fuzzy-PID controller. The first one called Single Input Fuzzy Inference Motor (SIFIM). This motor has one input with a separate SIFIM defined for each state variable (9 SIFIMs) and each input item \( X_i : i = 1, 2, 3, 4, 5, 6, 7, 8, 9 \) is fed into the corresponding SIFIM-i. The second fuzzy inference motor is Prefer Fuzzy Inference Motor (PFIM) that is used for the control priority order of each state variable. For \( X_i : i = 1, 2, 3 \) PFIM blocks take the absolute values of the input item \( X_2 \) as their antecedent variables. For \( X_i : i = 4, 5, 6 \) PFIM blocks do similar toward input item \( X_3 \), and PFIM blocks for \( X_i : i = 7, 8, 9 \) do the same for input item \( X_3 \).

Table 6

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Value</th>
<th>Design variable</th>
<th>Value</th>
<th>Design variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_h )</td>
<td>0.00010</td>
<td>( k_m )</td>
<td>0.00495</td>
<td>( k_n )</td>
<td>0.00002</td>
</tr>
<tr>
<td>( K_h )</td>
<td>0.97563</td>
<td>( K_m )</td>
<td>0.08541</td>
<td>( K_n )</td>
<td>-0.00017</td>
</tr>
<tr>
<td>( K_{h0} )</td>
<td>0.20740</td>
<td>( K_{m0} )</td>
<td>0.99996</td>
<td>( K_{n0} )</td>
<td>0.01493</td>
</tr>
<tr>
<td>( K_{h1} )</td>
<td>0.14633</td>
<td>( K_{m1} )</td>
<td>0.00743</td>
<td>( K_{n1} )</td>
<td>0.00233</td>
</tr>
<tr>
<td>( K_{h2} )</td>
<td>0.03882</td>
<td>( K_{m2} )</td>
<td>1.21991</td>
<td>( K_{n2} )</td>
<td>0.12165</td>
</tr>
<tr>
<td>( K_{h3} )</td>
<td>0.00048</td>
<td>( K_{m3} )</td>
<td>0.00126</td>
<td>( K_{n3} )</td>
<td>0.07167</td>
</tr>
</tbody>
</table>

Fig. 16. 3-D pareto front by objectives 4, 5, and 6 of optimal fuzzy-PID for orientational phase of chaser spacecraft.
The membership functions of SIFIMs for spacecraft system are shown in Table 2 and Fig. 5. The rules of the SIFIMs are as Table 3.

For the spacecraft system, \( f_s \), the output of SIFIM-i, is calculated from Eq. (3).

\[
\begin{align*}
 f_s &= V_A \times f_{s1} + P_O \times f_{s2} + Z_B \times f_{s3} \\
 &= \frac{V_A + P_O + Z_B}{V_A + P_O + Z_B}
\end{align*}
\]  

(3)

The membership functions of PFIMs for the spacecraft system are shown in Table 4 and Fig. 6. The rules of the PFIMs are tabulated in Table 5.

Table 7

<table>
<thead>
<tr>
<th>Point</th>
<th>Objective function</th>
<th>Value</th>
<th>Point</th>
<th>Objective function</th>
<th>Value</th>
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<tr>
<td>A</td>
<td>O.F.1</td>
<td>272.151</td>
<td>B</td>
<td>O.F.1</td>
<td>31.799</td>
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<td></td>
<td>O.F.2</td>
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<td></td>
<td>O.F.2</td>
<td>120470.491</td>
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<td></td>
<td>O.F.3</td>
<td>5746.200</td>
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<td>C</td>
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<td>D</td>
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<td></td>
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<td>G</td>
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<td>O.F.2</td>
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<td>O.F.6</td>
<td>1.248</td>
<td></td>
<td>O.F.6</td>
<td>66.714</td>
</tr>
</tbody>
</table>

For the spacecraft system \( \Delta W_1, \Delta W_2, \Delta W_3, \Delta W_4, \Delta W_5, \Delta W_6, \Delta W_7, \Delta W_8 \), and \( \Delta W_9 \) (The outputs of SIFIM-i), are obtained from Eq. (4).

\[
\begin{align*}
\Delta W_1 &= \Delta W_2 = \Delta W_3 = \Delta W_4 = \Delta W_5 = \Delta W_6 = \Delta W_7 = \Delta W_8 = \Delta W_9 \\
\frac{W_1 \times HS + W_2 \times HM + W_3 \times HB + W_4 \times HS + W_5 \times HM}{HS + HM + HB} \\
\ldots + W_6 \times HB + W_7 \times HS + W_8 \times HM + W_9 \times HB \\
\frac{HS + HM + HB}{(4)}
\end{align*}
\]

(4)

Given \( f_s \) and \( \Delta W_i \), it is likely to introduce the fuzzy-PID controller as Eq. (5):

\[
f = K_p \int \hat{\theta} dt + K_p \hat{\theta} \frac{d\hat{\theta}}{dt} + K_d \frac{d\hat{\theta}}{dt} + K_i \int \hat{\psi} dt + K_i \hat{\psi} + K_d \frac{d\hat{\psi}}{dt}
\]

(5)

where \( f \) is the control action:

\[
\begin{align*}
\hat{\theta} &= f_1, \\
\hat{\theta} &= f_2, \\
\hat{\theta} &= f_3, \\
\hat{\theta} &= f_4, \\
\hat{\theta} &= f_5, \\
\hat{\theta} &= f_6
\end{align*}
\]

\( \Delta W_i \) denote the fuzzy variables found by the Eqs. (6)–(14):

\[
\begin{align*}
\hat{\theta} &= K_{\theta 0} + K_{\theta 1} \Delta W_1 \\
\hat{\theta} &= K_{\theta 2} + K_{\theta 3} \Delta W_2 \\
\hat{\theta} &= K_{\theta 4} + K_{\theta 5} \Delta W_3 \\
\hat{\theta} &= K_{\theta 6} + K_{\theta 7} \Delta W_4 \\
\hat{\theta} &= K_{\theta 8} + K_{\theta 9} \Delta W_5
\end{align*}
\]  

(6)

Fig. 17. The position of chaser spacecraft in \( \theta \)-direction for optimum design points A, B, C, D and E illustrated in the pareto front.
\[ K_{db} = K^b_{db} + K^r_{db} \Delta W_b \]  
(11)

\[ K_{db} = K^b_{db} + K^r_{db} \Delta W_b \]  
(12)

\[ K_{db} = K^b_{db} + K^r_{db} \Delta W_b \]  
(13)

\[ K_{db} = K^b_{db} + K^r_{db} \Delta W_b \]  
(14)

in which \( K^b_{db}, K^r_{db}, K^b_{dh}, K^r_{dh}, K^b_{di}, K^r_{di}, K^b_{dw}, K^r_{dw} \) and \( K^b_{dw}, K^r_{dw} \) denote the base variables and \( K^b_{ri}, K^r_{ri}, K^b_{rh}, K^r_{rh}, K^b_{rdh}, K^r_{rdh}, K^b_{rw}, K^r_{rw} \) and \( K^b_{rw}, K^r_{rw} \) denote the regulation variables. Usually, the base and regulation variables can be found by trial and error.

Compared with other standard optimization methods, Genetic algorithm has important superiorities:

- Parallel computing is one of the main features of genetic algorithm, i.e. in this method in a certain time a population is moved toward optimal point rather than a single variable. As a result, convergence speed of this method increases significantly.
- In this method, one can optimize non-smooth behavior problems (e.g. functions with cyclic periods which have lots of relative minima or functions with highly nonlinearity) with acceptable scale.
- It's an efficient tool for the problems dealing with discrete variables.

3. Results and discussion

Here, the multi-objective optimization of the proposed Fuzzy-PID controller would be done with respect to nine design variables and six objective functions. The base values \( K^b_{dh}, K^b_{di}, K^b_{dw}, K^b_{dh}, K^b_{di}, K^b_{dw} \) and \( K^b_{dw} \) and regulation values \( K^r_{dh}, K^r_{di}, K^r_{dw}, K^r_{dh}, K^r_{di}, K^r_{dw} \) and \( K^r_{dw} \) are the design variables. The angular error of the spacecraft in the \( \theta - \varphi - \psi \) of “Euler-axis/angle” description and the control effort in corresponding directions are the objective functions. In summary, the objective functions are as Eqs. (15)–(20):

\[ O.F.1 = \int |x|dt \]  
(15)

\[ O.F.2 = \int |y|dt \]  
(16)

\[ O.F.3 = \int |z|dt \]  
(17)

\[ O.F.4 = \int |u_1|dt \]  
(18)

\[ O.F.5 = \int |u_2|dt \]  
(19)

\[ O.F.6 = \int |u_3|dt \]  
(20)

Table 8
Output of proposed controller of the point A in directions of Euler angles.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Settling time (s)</th>
<th>Maximum overshoot (deg)</th>
<th>Maximum angular velocity (deg/s)</th>
<th>Maximum driving force (N m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi )</td>
<td>150</td>
<td>5.9</td>
<td>3.6</td>
<td>0.52</td>
</tr>
<tr>
<td>( \phi )</td>
<td>120</td>
<td>0.35</td>
<td>1.7</td>
<td>0.005</td>
</tr>
<tr>
<td>( \psi )</td>
<td>212</td>
<td>113</td>
<td>23.7</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Fig. 18. The angular velocity of chaser spacecraft in \( \varphi \)-direction for optimum design points A, B, C, D and E illustrated in the pareto front.

Fig. 19. The driving momentum of chaser spacecraft in $h$-direction for optimum design points A, B, C, D and E illustrated in the pareto front.

Fig. 20. The position of chaser spacecraft in $\phi$-direction for optimum design points A, B, C, D and E illustrated in the pareto front.
Fig. 21. The angular velocity of chaser spacecraft in $\phi$-direction for optimum design points A, B, C, D and E illustrated in the pareto front.

Fig. 22. The driving momentum of chaser spacecraft in $\phi$-direction for optimum design points A, B, C, D and E illustrated in the pareto front.
Fig. 23. The position of chaser spacecraft in $\psi$-direction for optimum design points A, B, C, D and E illustrated in the pareto front.

Fig. 24. The angular velocity of chaser spacecraft in $\dot{\psi}$-direction for optimum design points A, B, C, D and E illustrated in the pareto front.
In this problem, the algorithm configuration of the genetic algorithm is as follows. The crossover fraction = 0.8, population size = 500, selection function = tournament, mutation function = constraint dependent, crossover function = intermediate, crossover ratio = 1, migration direction = forward, migration fraction = 0.2, migration interval = 20, distance measure function = distance crowding, Pareto front population function = 0.35, and stopping criteria is defined as function tolerance = $10^{-4}$.

To compare and make a precise view of objective functions, 3D pareto frontiers by different conflicting objective functions for the points A, B, C, D, E, F and G are shown in Figs. 7–16.

Design variables for the optimum design point A and objective functions for the optimum design points are given in Tables 6 and 7, respectively.

Complete stabilization occurs where all the state variables converge to zero. Settling time for optimum point A in the orientation task of docking manoeuvre is 360 s, and the maximum driving momentum is around 0.752 N m.

Among all the optimum points as outputs of GA, point B has the infimum value in direction of the axis namely objective function 1. This is the best point for objective 1 in all the figures. The points B, C, D, E, F and G have infimum values in directions of objective functions 2, 3, 4, 5 and 6 axes. These are the best points for objectives 2, 3, 4, 5 and 6 among all the output points of optimization. By adding objectives 1 to 6 with equal weighting factors, point A is the best point where its corresponding design variables, controls system with minimum possibly overshoot and settling time.

Angular position of chaser spacecraft in direction of $\theta$ is shown in Fig. 17 for all the points of A, B, C, D, E, F and G. Design variables related to point E as an optimum point to the objective 5, provide a controller which is not able to control system in directions of $\theta$, $\phi$ and $\psi$. However, points A, C, D and F as design points causes fully control of system in all directions. By evaluating control effort of these four design points, points A and B have the minimum and maximum control effort, respectively. The value of settling time, maximum overshoot, maximum angular velocity and maximum required control effort for point A in directions of $\theta$, $\phi$ and $\psi$ is shown in Table 8 (see Figs. 18–25).

Michael et al. [36] have reported the same results. Their work is similar to this paper except the point that the chaser is in a non-rotated initial state and its angular velocity is zero upon start of the manoeuvre. Unlike the chaser, the target also starts in a
non-rotating initial state and rotates with a constant angular velocity of $\frac{3}{2}$ \textdegree/s around its y axis which leads to a stable motion with respect to the time. The assumptions of initial values are as follows:

$$
\begin{bmatrix}
    x_0 \\
    y_0 \\
    z_0 
\end{bmatrix} =
\begin{bmatrix}
    0 \\
    3 \\
    0 
\end{bmatrix},
\begin{bmatrix}
    v_{x0} \\
    v_{y0} \\
    v_{z0} 
\end{bmatrix} =
\begin{bmatrix}
    0 \\
    0 \\
    0 
\end{bmatrix},
\begin{bmatrix}
    \omega_x \\
    \omega_y \\
    \omega_z 
\end{bmatrix} =
\begin{bmatrix}
    0 \\
    0 \\
    0.052395(\text{rad}) 
\end{bmatrix}
$$

To make a real comparison, output results of Michael’s work for Orientation, angular velocity and momentum control of target and chaser is demonstrated in Figs. 26–28, respectively.

Although there are some differences between our work and Michael et al. [36] in initial conditions assumptions for target and chaser, the objective of research is the same. By comparison of these two works, superiority of our work from viewpoints of distance error, angle error and control effort decrease is distinct.

In orientation task, as shown in Fig. 26, Michael’s work focus on a tracking problem. It reached to the final state almost in 270 s, 360 s and 270 s in $\theta$, $\phi$ and $\psi$ directions, respectively, while we can achieve it almost 150 s in $\theta$ direction, 120 s in $\phi$ direction and 212 s in $\psi$ direction, which is far better. As shown in Fig. 28, obviously, there is no off time for momentum wheels in Michael’s work and they need more energy to run compared to our work.

4. Conclusion

In this study, designing a Fuzzy-PID controller using GA was successfully exploited for orientational phase of docking maneuver of two spacecraft problem. A designed FPID controller for stabilization purpose of orientational phase of a docking maneuver is presented based on the SIFIMs dynamically connected PFIM for each direction. The inputs of the controller are the error of Euler’s angles and angular velocities of the chaser and the driving force is set as its output. In this work, the angular error of the spacecraft in the $\theta-\phi-\psi$ of “Euler-axis/angle” description and the control effort in corresponding directions are chosen as critical fitness functions of genetic algorithm. To avoid saturation of actuators, the constraint of maximal of the momentum produced by momentum wheels is added to optimization problem. By constructing this novel optimal fuzzy-PID controller, chaser spacecraft would fulfill its task in less possible time and minimum propellant consumption. Generally, in this work, performing docking maneuver with the least control effort, accurate pointing and settling time decrease was considered in the purpose of controller design process. The reported result indicated that expected controller can effectively response well to the given constraints and conditions. In comparison with similar works, some of system parameters like settling time are improved, overshoot (as a critical parameter in soft-docking maneuver) is decreased and the less amount of energy is required.

References


