Translational Controller of Spacecraft Formation Flying using Adaptive Intelligent Control

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Abstract
Autonomous rendezvous and proximity operations of satellites in formation are the most advanced technologies in space missions. This paper presents a formation flight control of the relative translational dynamics of satellites moving in circular orbits around the Earth. The relative dynamical model for this formation flying problem is derived in Hill's frame based on Clohessy –Wiltshire (CW) equations. A tracking control problem of relative translational motion between two satellites in a leader-follower scheme has been discussed using an intelligent PID controller. This controller is implemented in the linearized model while the follower satellite is actively controlled to perform the required movements to bring itself into the desired formation to the leader satellite. The gains of this controller are tuned using MATLAB genetic algorithm (GA) toolbox to enhance the performance of the system. The simulation results compare the performance of both traditional and intelligent PID that clarify good control precision and the effectiveness of the proposed controller (GA-PID) in solving the spacecraft formation problem.

I. INTRODUCTION

In recent years there has been an increased interest in formation-flying satellites and autonomous docking. These formation-flying satellites offer potentially greater scientific and operational capabilities than those attainable with a monolithic spacecraft [1]. Satellite formation flying is defined as a set of more than one satellite whose dynamic states are coupled through a common control law [2]. It represents a new idea in space mission design which is achieved by replacing large satellites with multiple small satellites which has some benefits such as low cost, high performance, flexibility, modularity, and multi-mission capabilities [3]. These qualities make them ideal for astronomy, communications, meteorology, and environmental uses. However, the main challenge for tight spacecraft formation flying lies in the coordination of the spacecraft motions relative to each other, to avoid inter-satellite interference, and collisions, and achieve mission goals with minimum control efforts [4]. As a result, some automatic control methods for flying spacecraft in formation have been developed for the sake of minimizing the costs and risks associated with large, single-spacecraft missions [5].

In this paper, relative dynamical models of formation flying were introduced, and Hill equations were deduced considering the circular reference orbit. Based on the linear state space model of relative dynamics, an intelligent PID controller tuned by a genetic algorithm has been implemented for tracking control of relative translational motion between two spacecraft in a leader-follower formation.

The rest of this paper is organized as follows: Section (II) outlines the dynamic model for the leader-follower spacecraft formation. Section (III) presents the formulation of the proposed GA-PID controller. Then the analysis of the simulation results is discussed in Section (V). Finally, the conclusion is presented.

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II. DYNAMIC MODEL

The simplest known model for the relative motion between two satellites is described using the Hill-Clohessy-Wiltshire (HCW) equations which offer some periodic solutions that are of particular interest to formation flying. The equations are deduced under the assumptions that the Earth is a perfect sphere and that the Leader satellite is in a Keplerian circular orbit. For a satellite orbiting the Earth, the two-body problem applies, under the assumptions that the equations of motion are expressed in a non-inertial reference frame whose origin coincides with the center of mass of the central body, Both the central body and satellite are homogenous spheres or points of equivalent mass and the inverse-square gravitational force between the two bodies is the only force in action [3].

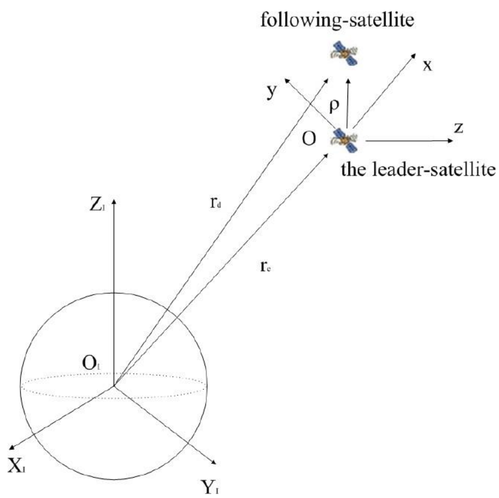

Fig.1: Schematic diagram of the relationship between the leader satellite and the following satellite.

The dynamic model of a satellite in any orbit can be obtained according to Kepler's equation [4]:

$$\ddot{r} + \frac{\mu}{r^3}\vec{r} = 0 \tag{1}$$

Where $\vec{r}$ represents the radial vector from the earth's center of mass to the satellite, μ is the gravitational constant, $\mu=GM$, with M as the Earth's mass. Based on Fig.1, the equations of motion of the leader and the following satellite. Respectively, can be obtained as:

$$\ddot{r} + \frac{\mu}{r_C^3}\vec{r_C} = 0 \tag{2}$$

$$\ddot{r_d} + \frac{\mu}{r_d^3}\vec{r_d} = f \tag{3}$$

In equation (3), f is the sum of perturbation and control forces exerted on the satellite [3], ρ as the relative distance between the center of the leader satellite and the center of the following satellite where $\rho = x\vec{i} + y\vec{j} + z\vec{k}$. Then:

$$\ddot{\rho} = \ddot{r_d} - \ddot{r_C} = \frac{\mu}{r_C^3}\vec{r_C} - \frac{\mu}{r_d^3}\vec{r_d} + f \tag{4}$$

$$\ddot{r_d} - \ddot{r_C} = \mu r_c^{-3}[\vec{r_C} - (1 + \frac{2y}{r_c} + \frac{\rho^2}{r_c^2})^{-3/2}(\vec{\rho} + \vec{r_C})] + f \tag{5}$$

From equations (4) and (5) and based on the assumptions that no external perturbations act on both leader and following satellites, the radial separation between the leader satellite and the following satellite is very small compared to the radius vector of the leader satellite from the center of Earth ($\rho \ll r_C$) and considering the leader satellite runs in a circular reference orbit. The simplified linearized form of Clohessy-Wiltshire equations of relative motion of two satellites in Hill's frame can be deduced as [4]:

$$\begin{aligned} \ddot{x} &= 2w\dot{y} + 3w^2x + f_x \\ \ddot{y} &= -2w\dot{x} + f_y \\ \ddot{z} &= -w^2 z + f_z \end{aligned} \tag{6}$$

Where w denotes orbital angular velocity and f_x , f_y , f_z represent the orbit control force.

The State-Space representation for the relative linear dynamics used in this study is given by [5]:

$$\begin{aligned} X &= AX(t) + Bu(t) \\ Y &= CX(t) \end{aligned} \tag{7}$$

Where $X,\ u$ denote system relative state and input vectors, respectively, and Y denote output vector. A is the state coefficient matrix, B is the control coefficient matrix and C is the output coefficient matrix [6].

$X = [x\ y\ z\ v_x]^T$ $\quad u = [f_x\ f_y\ f_z]^T$

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & & & & \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 3w^2 & 0 & 0 & 0 & 2w & 0 \\ 0 & 0 & 0 & -2w & 0 & 0 \\ 0 & 0 & -w^2 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

, and $C = diag([1\ 1\ 1\ 1\ 1\ 1])$

III. GA- PID CONTROLLER DESIGN

The general form of PID controller is given as follows [7]:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dx} \quad (8)$$

$$e(t) = Ref.Value\,(R) - Actual.output\,(y) \quad (9)$$

The aim is to minimize the error signal which is defined as the difference between the desired target and actual output of the system at any particular instance that is achieved by proper tuning of k_p, k_i, k_d gains of PID controller. The proportional term (k_p) has the main effect in changing the output value as its output proportional to the current error value of the system. The integral term (k_i) sums up all the past error values and controls the speed by which the system steady-state error is reduced. The derivative term (k_d) estimates the controller's future response depends on the rate of change in error value over time and works on damping reduction, enhancing the stability, and obtaining a smooth response. Thus, all three coefficients need to be tuned to force the output response of the control system output to track the desired state.

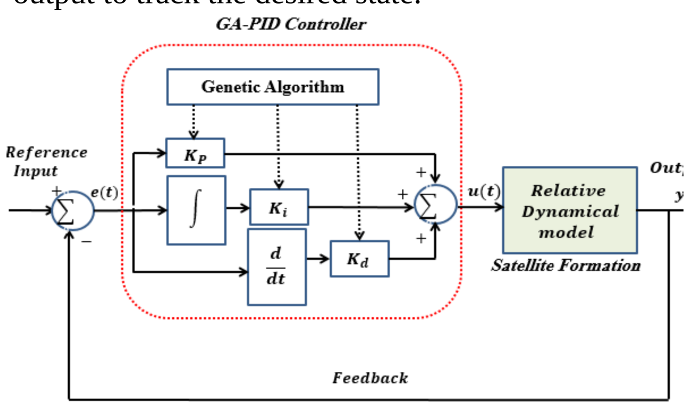

Fig.2: schematic diagram for the proposed GA-PID controller.

For our formation flying case study, as shown in Fig.2 the working process can be interpreted as follows: the translational control forces $u(t)$ will be sent to the follower spacecraft needed to control, then the new signal output $y(t)$ will be obtained. Subsequently, the feedback is needed to take in a period to find the new error signal $e(t)$. Based on this new error signal, the PID controller whose gains are tuned using MATLAB genetic optimization toolbox computes to give the new control signal and the process keeps going on to accomplish a stable satellite formation flying [8].

IV. RESULTS AND DISCUSSION

Simulation for the relative dynamical model of satellite formation flying expressed in equation (6), has been performed in MATLAB/Simulink environment. In this work, Hill's frame represents the relative motion of a follower satellite B for the leader satellite A. Fig.3 depicts the orbital motion of the two satellites A and B, in the three-dimensional space of the inertial Earth frame. Also, Fig.4 visualize how the follower spacecraft B appears when seen from the origin of Hill's frame while both satellites are in formation flying.

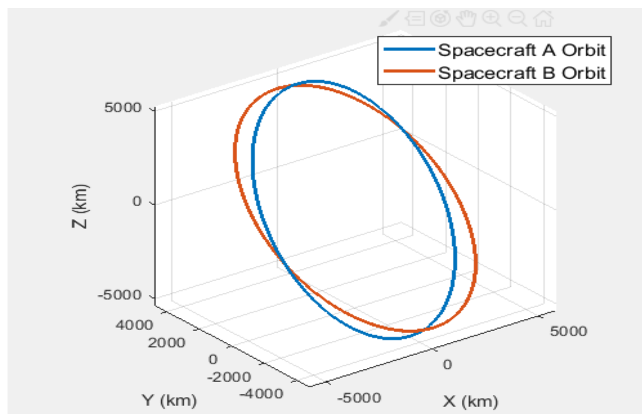

Fig.3: Orbital motion of satellites A and B under the influence of Earth's gravity.

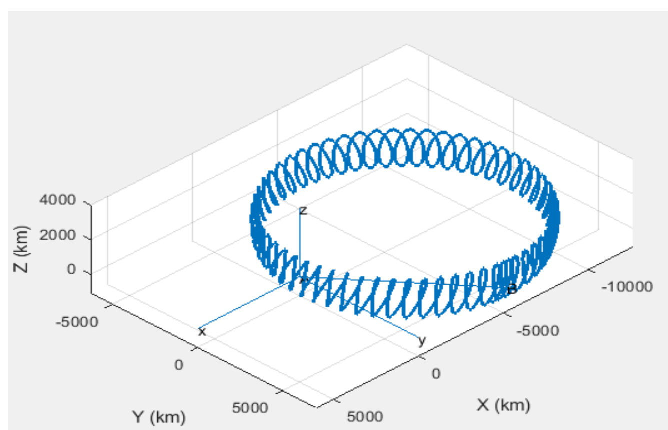

Fig.4: Relative motion of follower satellite B for a leader satellite A in Hill's Frame.

The simulation results compare the performance of the traditional PID and GA-PID controller whose gains are tuned by a genetic algorithm. These controllers are implemented to solve the formation problem of spacecraft. Based on that, some initial and final relative position conditions for the relative dynamical model are given:

$$x(t_0) = -0.906\ km \qquad x_f(t) = -2.32\ km$$

$$y(t_0) = -0.845\ km \qquad y_f(t) = 8.85\ km$$

$$z(t_0) = -0.906\ km \qquad z_f(t) = 5.37\ km$$

The orbital parameters selected for the leader satellite are circular as tabulated in Table (1) The relative conditions of the follower satellite [ρ, φ] are commanded from the initial value [1km, 245◦] to the final desired value [5km, 260◦].

Orbital parameters	Value
Semi-major axis (a)	10,000km
Eccentricity (e)	0
Orbit inclination (i)	60
Argument of perigee (ω)	0
Longitude of ascending node (Ω)	0
Initial true anomaly (ν)	0

Table (1): leader satellite orbital parameters

The response of x, y, and z relative positions for both traditional PID and intelligent GA-PID controllers implemented to achieve the desired states are depicted in Fig.5 and Fig.6, respectively. The results clarify that the intelligent controller GA-PID has small relative position error, smooth response, and efficient performance without any fluctuations or overshoots compared to the traditional PID controller.

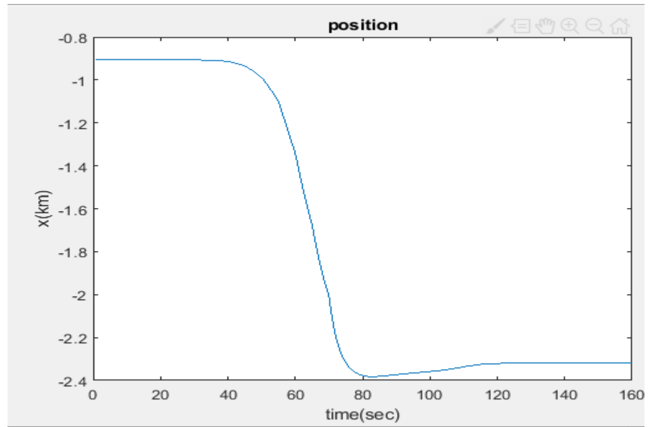

Fig.5a: Relative movement in x direction for traditional PID controller.

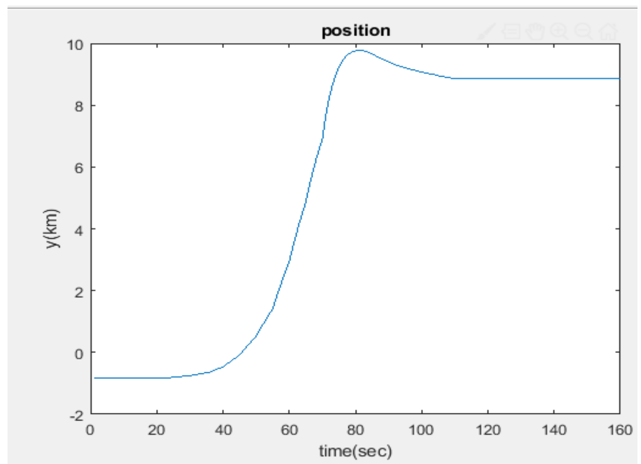

Fig.5b: Relative movement in the y direction for traditional PID controller.

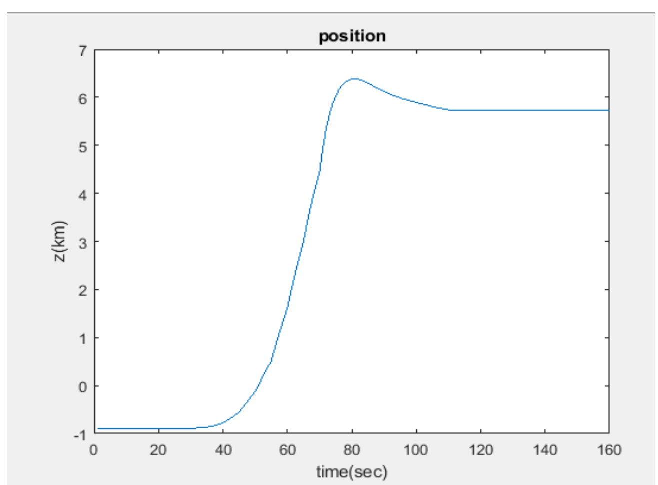

Fig.5c: Relative movement in the z direction for traditional PID controller.

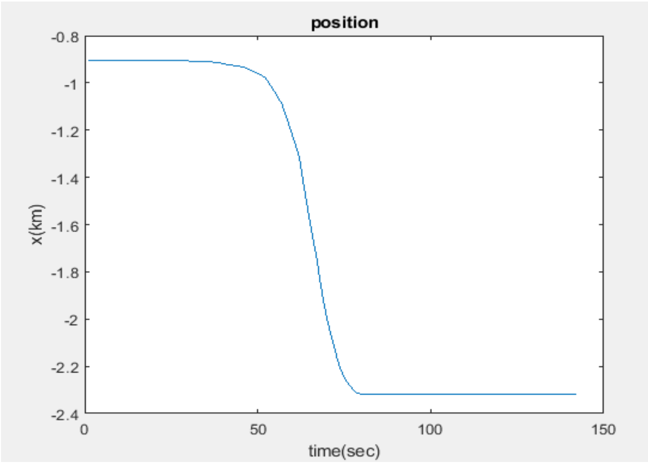

Fig.6a: Relative movement in the x direction for intelligent GA-PID controller.

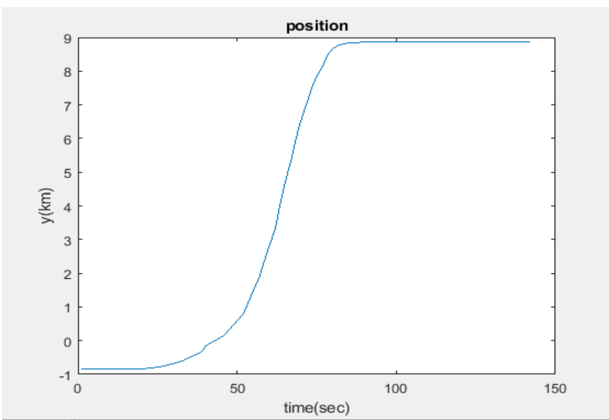

Fig.6b: Relative movement in the y direction for intelligent GA-PID controller.

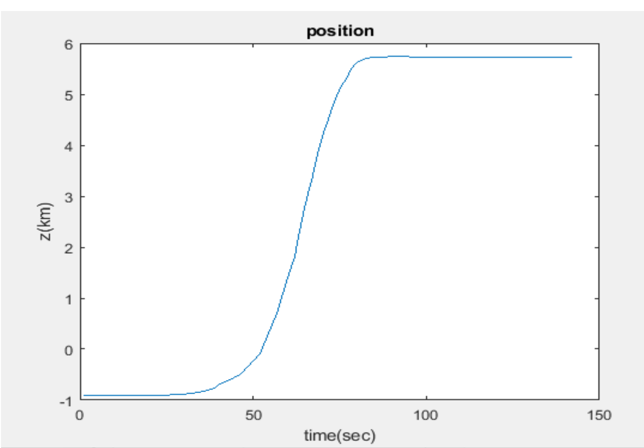

Fig.6c: Relative movement in the z direction for intelligent GA-PID controller.

V. CONCLUSIONS

This paper discussed a tracking control problem of relative translational motion between two satellites moving in circular orbits around the Earth in a leader/follower formation. A translational controller (GA-PID) is implemented to the derived linear dynamical model of the relative translational position of spacecraft formation flying. Simulation results were performed in a MATLAB/Simulink environment that clarifies the smoothness and efficient performance of the proposed intelligent controller in solving the spacecraft formation problem.

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