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Tuning of Pulse-Width Pulse-Frequency Modulator using PSO: An Engineering Approach to Spacecraft Attitude Controller Design

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Original scientific paper

In this paper, a new technique for fine tuning of spacecraft autopilots based on pulse-width pulse-frequency (PWPF) modulators is presented. PWPF is one of the most commonly used approaches to control signal modulation. Its main application is found in spacecraft controllers to produce discontinuous on-off control signals for two situational actuators. The main reasons for the popularity of this method are the reduced energy consumption and the quasi linear operation with high degrees of freedom in adjustment. But, due to multiplicity and nonlinear relationship between parameters, fine tuning of PWPF is known to be an engineering problem. Similar complexity is observable in adjusting the incorporated controller parameters. These involvements regarding the industrial and academic background of PWPF are not properly explored. The paper shows how particle swarm optimization (PSO) can be invoked to set both controller and PWPF parameters. Several spacecraft autopilots have been designed to show effectiveness of the proposed method.

Key words: Spacecraft attitude control, Controller tuning, Particle Swarm Optimization (PSO), Pulse width pulse modulation (PWPF)

Podešavanje pulsno-širinskog pulsno-frekvencijskog modulatora korištenjem optimizacije rojevima čestica: Inženjerski pristup dizajnu regulatora orijentacije letjelice. U ovom radu prikazana je nova metoda za fino podešavanje autopilota letjelice zasnovana na pulsno-širinsko pulsno-frekvencijskoj modulaciji (PWPF). PWPF je jedan od najčešće korištenih pristupa u upravljanju modulacijom signala. Njegova glavna primjena nalazi se u regulatorima letjelica koji proizvode diskontinuirane on-off upravljačke signale za dva aktuatora. Glavni razlozi za popularnost ove metode je smanjena potrošnja energije i kvazi linearno ponašanje s velikim stupnjem slobode kod podešavanja. Međutim, zbog višestrukosti i nelinernih odnosa među parametrima, fino podešavanje PWPF-a je zahtjevno. Slična složenost može se primijetiti i kod podešavanja parametara regulatora. Ovi problemi kod primjene PWPF-a nisu dovoljno istraženi. U ovom radu prikazano je kako se može iskoristiti optimizacija rojevima čestica za podešavanje parametara regulatora i modulatora. Dizajnirano je nekoliko autopilota letjelica kako bi se pokazala učinkovitost predložene metode.

Ključne riječi: upravljanje orijentacijom letjelice, podešavanje regulatora, optimizacija rojevima čestica, pulsno-širinska pulsna modulacija

1 INTRODUCTION

Spacecraft controllers have gained great attentions in the history of aerospace industries and academies owing to their interesting and challenging points. Stabilization is the basic principle; however, the spacecraft attitude should be able to turn to a specific situation. To this end, several instruments such as reaction wheels, control moment gyros, gas generators etc. have been utilized in attitude controllers. In the past years, diverse control algorithms have been implemented and the classic methods are still dominant [1-3]. But more sophisticated and modern methods like adaptive and robust adaptive control [4,5], variable structure control [6,7], model predictive control [8] etc. have been investigated through technology progression to deal with realistic problems such as poorly damped flexible modes, model uncertainties and unknown disturbances.

Usually, limitations in the size, weight, and reserved power restrict the applicable control mechanisms which impose on-off actuation system. These actuators can operate in on, off and opposite-on states. Besides using this type of mechanisms, the computed control signal needs to be discretized and translated properly into on-off situations. For this purpose, several approaches such as bang-bang controller, pulse width modulators and their derivatives have been proposed and examined [1,2]. Maybe, the most famous and commonly used method is pulse-width pulse-frequency (PWPF) modulation. Reduced energy consumption and quasi linear operation with high degrees of freedom in adjusting are the attributes of this modulator. However, nonlinear blends between parameters of PWPF with integrated plant-controller dynamics compel some difficulties in fine-tuning of total selectable knobs. In this paper, an artificial intelligence method is first proposed to solve the engineering complication of PWPF-based spacecraft controllers.

Controller tuning is an important stage in design procedure of control systems. Each controller, at least, at final stage has to be fine-tuned. Specially, whenever there are lots of versatile knobs which are related nonlinearly, the tuning routine can be challenging and time consuming. Also, in engineering issues, automatic tuning is valuable and sometimes causes an optimization issue. Nowadays, applications of swarm intelligence techniques are identical and increasing to cope with engineering tasks [9]. Meanwhile, particle swarm optimization (PSO) due to some features has attracted many attentions in system identification and control [10-15]. Kennedy and his co-workers proposed this powerful stochastic optimization method based on the social behaviour of birds within a flock [16,17]. This approach has several superior advantages such as simplicity, low computational burden with promising optimization results which currently turned it to one of the applicable and popular techniques amongst engineering optimization methods. In [18], a version of PSO is utilized for robust setting of Proportional-Derivative-Integral (PID) controllers based on H? technique. In [19], PSO is invoked for gain adaptation of a self-tuning proportional-integral (PI) controller for a static synchronous compensator. References [12] and [15] have used this optimization method for tuning fuzzy PID and Model Predictive controllers, respectively. Moreover, in [20], automatic fighter tracking variable feedback gains are determined using PSO. Also, [21,13,14] have shown the applications of PSO in system identification area. As the main contribution, the paper shows how this optimization method can be employed for setting of PWPF based spacecraft controllers. Moreover, several simulation scenarios are conducted to show effectiveness of the proposed methodology.

The rest of the paper is arranged as follows. Section 2 discusses the problem statement. In section 3, particle swarm optimization technique is explained, then, simulation results of the proposed method are presented in Section 4. Finally, the concluding remarks are illustrated in Section 5.

2 PROBLEM STATEMENT

Figures should be ideally in 300 dpi resolution.

As noted earlier, on-off thrusters are popular in spacecraft attitude controllers but producing proper on-off commands from calculated continuous control signals is quite stimulating. Several methods have been proposed for this aim amongst which pulse-width pulse frequency (PWPF) modulator is the most famous. This modulator has been used practically in several communication satellites such as INTELSAT-V, INSAT, and ARABSAAT [22,23]. General concept of spacecraft attitude control system is shown in Fig. 1.

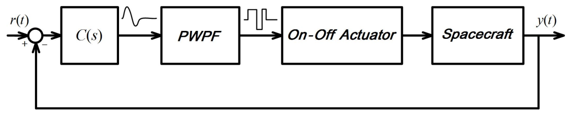

Fig. 1. Schematic spacecraft attitude loop with on-off actuator and PWPF modulator

According to Figure 1, PWPF modulator converts computed control signals into on-off levels. Advantages of this modulator were analysed in several researches which show low sensitivity to perturbations, high degree of freedom in adjusting, reduced fuel consumption etc. [24-26]. Dealing with PWPF-based controllers, persistently, has been an interesting subject in the six past decades [22, 26-33]. It has had historical analogous applications in the aerospace control systems and its features have been well known for designers [27,28,34]. Block diagram of PWPF modulator is displayed in Fig. 2. It is generally formed by a Schmitt trigger with a low-pass filter in a loop [26]. For appropriate setting of this modulator in a feedback loop, four parameters should be tuned properly. These parameters are: pre-filter gain (K_m) and time constant (τ_m) as well as activation (U_{on}) and deactivation (U_{off}) values of Schmitt trigger.

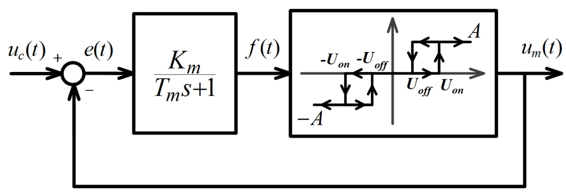

Fig. 2. Pulse-width pulse-frequency (PWPF) modulator

Progressively, PWPF-based controllers are getting more popular in control engineering literature [6,7, 29-33]. Hu and co-workers have examined several control methods such as variable structure and fault tolerant controller for flexible spacecraft implemented by PWPF [6,7,29,30]. Li and Peng in [32], used a combination of neural network-based sliding mode controller with PWPF for Mars entry vehicle. [33,35] analyzed the limit cycle and stability of PWPF-based controllers. Furthermore, in [23], another application has been clarified for controlling shape memory alloy actuators. Other instances can easily be found in the literature. In spite of these numerous attentions, sufficient investigations have not been offered on the manner of PWPF tuning. Only a few works have been done and some guidelines about the range of these parameters are recommended [6,7,25,35].

Due to the multiplicity of PWPF parameters and nonlinear associations between designed controller parameters and its alterable knobs, the issue causes an optimization problem and classical optimization methods encountered some problems in contrast with it. [24] proposed effective ranges for selectable knobs of PWPF and these guidelines are used successfully in some other applications [6,7,35]. In [25], the static and dynamic characteristics of PWPF modulator are analysed and some other recommendations have been proposed for optimal selection of PWPF parameters. Thanks to the lack of a straightforward relationship for parameters of PWPF, the recommended remedies are not general. Also, if the designer wants to adjust the controller and more PWPF parameters simultaneously, it can possibly change to a very time-consuming and difficult subject, even in the proposed areas of parameters. Then, this causes a nonlinear and non-trivial optimization task with no rigorous connections between parameters. Besides, fine-tuning of these parameters is an open topic. In this paper, PSO is properly used for tuning of PWPF and controller fixing variables. The proposed method is implemented on combined tuning problem of PID controller plus PWPF modulator for on-off control systems of various spacecraft. The obtained results show the effectiveness and high fidelity of the proposed strategy.

3 CONTROLLER TUNING METHOD

The particle swarm optimization (PSO) algorithm is a population-based search algorithm established for the simulation of the social behaviour of birds within a flock. In this algorithm, the individuals referred to particles are grouped into a swarm. Each particle in the swarm represents a candidate solution to the optimization problem. These particles adjust their positions by informing their own best position and one of the best particles to propel themselves towards an optimum solution. Compared with conventional optimization methods, PSO has some special features such as:

1. Except cost function calculator, it does not require other excessive information about optimization issue such as gradient, Hessian etc. and also it does not have other limiting conditions such as differentiability, convexity etc.;

2. It has the ability to run away local minima since it uses transition rules that are stochastic in nature;

3. It is computationally inexpensive;

4. It does not need to choose good initial conditions to converge since it is a population-based method.

These advantages make it a popular optimization tool for engineering circumstances. Specially, applications of PSO in control engineering have been reported in the introduction of this paper. The paper uses this optimization algorithm for appropriate choice of PWPF-based spacecraft autopilot. General concept is illustrated in Fig. 3. Controller and PWPF parameters can be adjusted by PSO by defining a proper cost function and employing a right scenario.

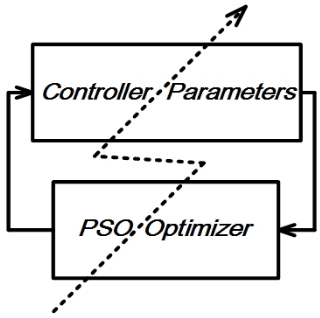

Fig. 3. Schematic diagram of controller tuning method

But this algorithm must be first depicted. As mentioned, PSO assigns an individual each one of the optimization parameters in a position vector space (x) and then modifies these vectors by means of such a velocity vector (v):

$$x_i(k+1) = x_i(k) + v_i(k+1). \tag{1}$$

to reach optimal values of parameters considering an objective function. In this equation, i is the number of particles and k is iterations. Several methods have been recommended for calculating velocity vector which produces several versions of PSO. In this paper, these relations have been exploited as star topology [9]:

$$\begin{aligned} &v_i(k+1) = w(k)\, v_i(k) + ... \\ &c_1 r_1 (pbest(k) - x_i(k)) + c_2 r_2 (gbest(k) - x_i(k)) \\ &w(k) = w_{\max} - \left(\tfrac{w_{\max} - w_{\min}}{Max.Iter.}\right).k \end{aligned} \tag{2}$$

Velocity vector (v) is changed in each step using value of its own best personal ($pbest$) position and the global best position ($gbest$) of all particles. An inertia factor (w) compromises the velocity vector to prevent random movement of the particles in the search space and to deviate the velocity of the particles by a smaller amount in each iteration. The two positive constants c_1 and c_2 are the cognitive learning rate and the social learning rate, respectively.

$\{r_1, r_2\} \in [0,1]$ are also two uniformly distributed random numbers. Upgrading position vector in (3) by updated velocity vector using relation (2) guides particles to find optimum value of themselves which satisfies cost function. The cost function is introduced in the next Section. Another restriction is enforced to maximum value of velocities for preventing large fluctuations of these vectors to control the global exploration of the particles [9]. These values are designated on 50% of the range in each particle's dimension.

4 SIMULATION RESULTS

In this Section, the proposed method is applied to tune PID-type attitude controller of various spacecraft models. In two initial simulations, only rigid body dynamics of spacecraft is considered [3,31,36], and the third simulation deals with a more sophisticated flexible model[2]. A PID-type controller with velocity feedback is utilized for pitch channel attitude controller. A typical block diagram of this controller is demonstrated in Figure 4.

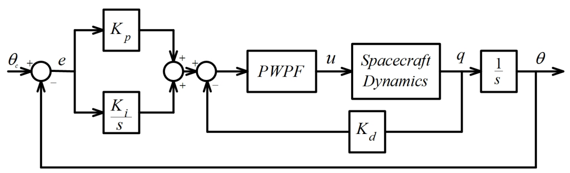

Fig. 4. PWPF-based PID Attitude control system for a spacecraft

The goal is to design a proper controller gains for satisfying this cost function:

$$J = \sum_{t=0}^{t_f} \left(w_e te\left(t\right)^2 + w_u \left|u\left(t\right)\right| \right). \qquad (3)$$

In this function, a combination of tracking error $(e\left(t\right))$ and control effort $(u_m\left(t\right))$ with w_e and $w_u$weights respectively are incorporated to search optimal values of seven alterable knobs $(Kp, Ki, Kd, K_m, \tau_m, U_{on}, U_{off})$ shown in Figures 2 and 4. t_f is the final time of simulation and t is the time in each step. It is notable that the optimization weights are chosen by the objectives of controller designer and they cause a trade-off between tracking error and allocated control energy. If one wants to emphasize on tracking error, increases the magnitude of error weight w_e or decreases energy weight w_u and vice versa. The optimization algorithm is not sensitive to these weights at all and diverse permutations of them only change the controller strategy in performance-energy conciliation, hence, they can be set by a very few trials. By determining the mentioned seven parameters, a proper controller can be designed. Now, for this purpose, both of the PID and PWPF parameters must be properly estimated using PSO to fulfil objective function (3) appropriately. For this purpose, three simulation scenarios have been carried out to show the potentiality of the new method.

Table 1. Search range for optimization parameters in example 1

Optimization Parameter	Search Range
Kp	$[1, 1000]$
Ki	$[1, 5]$
Kd	$[1, 1000]$
K_m	$[2, 10]$
τ_m	$[0.2, 2]$
U_{on}	$[0.1, 50]$
U_{off}	$[0.1, 50]$

Table 2. Optimized parameters for example 1

Optimization Parameter	Search Range
Kp	96.71
Ki	3.74
Kd	82.29
K_m	7.72
τ_m	0.20
U_{on}	0.43
U_{off}	0.35

4.1 Example 1:

At first simulation, rigid spacecraft dynamics in Fig. 4 is considered as: $G(s) = 1/Is$where $I = 11.4\ kg.m^2$is the spacecraft moment of inertia [26]. This model is relatively simple but it is prevalent in some practical applications. Also, the thruster level of force is supposed$A = 1\ N.m$. In this example, chosen variables have been initiated and clamped in rather wide ranges as Table 1.

Also, another constraint $U_{off} < 0.8 U_{on}$ has been considered by employing guidelines presented in [7,24]. The population contains 100 particles and simulation is run for a step response scenario with only 100 iterations using a cost function by$w_e = 10,\ w_u = 0.5$. Seven adaptable parameters are shown in Fig. 5. In addition, relevant cost function versus iterations is exhibited in Fig. 6. It can be observed that modifiable parameters have converged to the steady values and cost measure reaches an optimum quantity of $J = 0.062$.

As can be seen in these figures, the speed and precision of implemented algorithm are acceptable. By ending iterations, parameters converge to the values of Table 2.

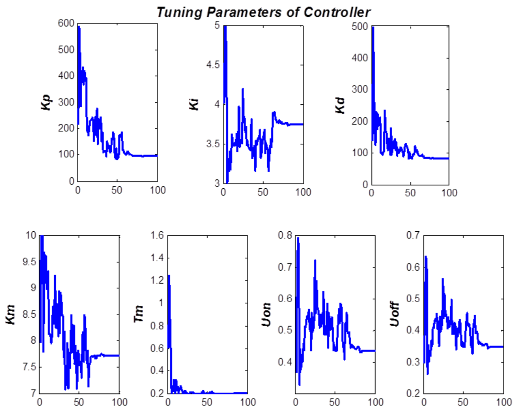

Fig. 5. Optimized parameters versus iterations for system for $I = 11.4\ kg.m^2$

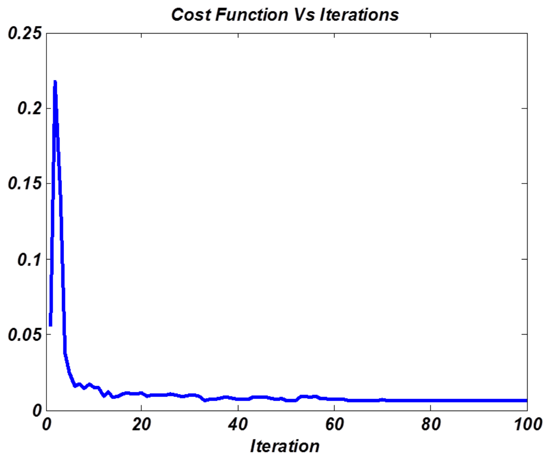

Fig. 6. Cost function versus iterations for system for $I = 11.4\ kg.m^2$

Note that, this simulation is repeatable for the selected number of particles and iterations. Performance of optimized parameters applied to the plant is illustrated in Fig. 7. Note that, transient and steady state behaviour of controller is good and system output tracks the set-point after three seconds with no overshoot and oscillation. These are identical by comparing results of [26]. Also, this performance is attained by a reasonable energy effort in control signal without any extra firings.

4.2 Example 2:

In this example, another spacecraft attitude model with $I = 1000\ kg.m^2$ and $A = 2\ N.m$ is considered from [36]. For this system, costing weights of $w_e = 10$ and $w_u = 0.1$ are used. Based on the large moment of inertia

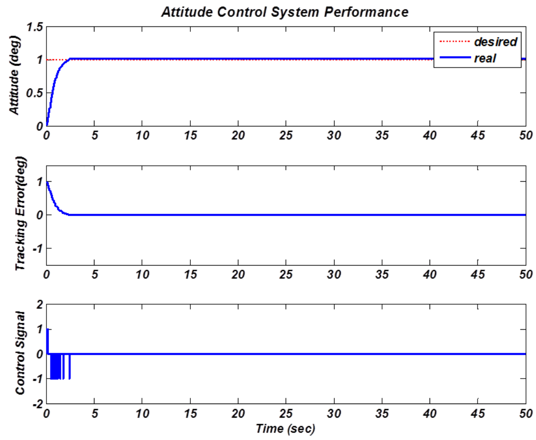

Fig. 7. Optimized controller performance for system for $I = 11.4\ kg.m^2$

causing low open loop system gain, the range of proportional and derivative gains is extended to $1 \leq Kp \leq 2000$ and $1 \leq Kd \leq 2000$. Of course, this makes the optimization problem harder. Other settings are the same as the pervious simulation. Note that in engineering applications, the designer usually does not search for these large ranges of adjustable variables due to his knowledge of system, then, the optimization is reduced to a fine-selecting problem. But as it will be seen, the proposed method can deal with this large area of parameters. Optimized parameters and related cost functions after 100 iterations are demonstrated in Figures 8 and 9. Figure 8 shows the convergence of parameters to steady values and Fig. 9 exhibits the tendency of objective function to an optimum value of $J = 0.0428$. Optimized parameters are presented in table 3.

Simulation results are gathered for this system in Figure 10. Desirable performance of tuned controller is obvious in this Figure. With a low time complexity and consuming a reasonable level of energy, the error signal converges to zero. The transition state also shows the performance of the proposed method. These results validate that presented technique is suitable for designing this type of controllers.

4.3 Example 3:

Two former simulations exerted ordinary models. To validate the effectiveness of the suggested method a more realistic system must be examined. To do this, yaw channel controller of INTELSAT V Spacecraft is regarded [2]. Beside rigid body dynamics, the system has three main flexible modes imposed by solar arrays indurating the controller designing procedure. Also, by enforcing improper pulse modulations, these elastic modes can create some

Table 3. Optimized parameters for example 2

Optimization Parameter	Search Range
Kp	931.07
Ki	0.78
Kd	1672.5
K_m	2.02
τ_m	0.20
U_{on}	0.20
U_{off}	0.16

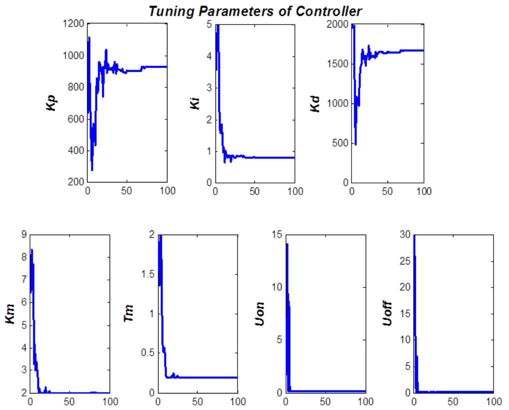

Fig. 8. Optimized parameters versus iterations for second system

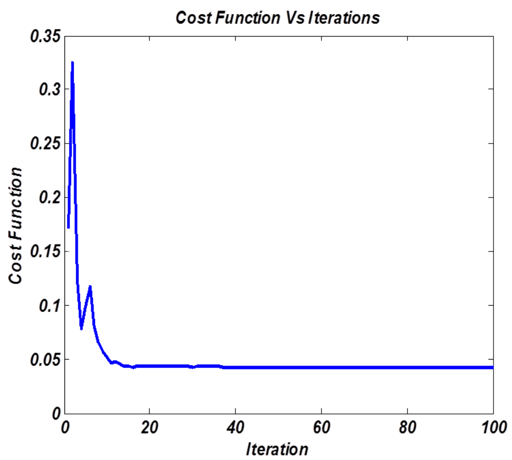

Fig. 9. Cost function versus iterations for second system

problems incorporated. A seventh order transfer function can describe the yaw channel model of this spacecraft [2]:

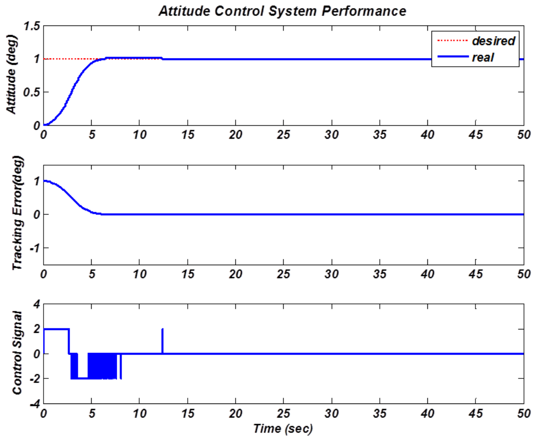

Fig. 10. Optimized controller performance for second system

Table 4. Optimized parameters for example 3

Optimization Parameter	Search Range
Kp	37480.30
Ki	0.18
Kd	97340.86
K_m	2.83
τ_m	0.0103
U_{on}	46.33
U_{off}	37.07

$$G = \frac{1}{Is}\frac{\left(s^2/z_1^2+2\xi s/z_1+1\right)\left(s^2/z_2^2+2\xi s/z_2+1\right)}{\left(s^2/p_1^2+2\xi s/p_1+1\right)\left(s^2/p_2^2+2\xi s/p_2+1\right)}\times \cdots \frac{\left(s^2/z_3^2+2\xi s/z_3+1\right)}{\left(s^2/p_3^2+2\xi s/p_3+1\right)}$$
$$\begin{cases} \xi = 0.002, & J = 2150 \;\; kg.m^2 \\ z_1 = 1.0\,, & p_1 = 1.1 \\ z_2 = 2.0, & p_2 = 3.5 \\ z_3 = 7.2\,, & p_2 = 7.3 \end{cases} . \quad (4)$$

In addition, on-off thrusters actuate these systems by levels of$A = 2 \;\; N.m$. The controller structure is the same as Figure 3 for yaw channel parameters instead of pitch parameters. For this system, due to relatively lower gain of plant, wider range for proportional and derivative gains $1 \leq Kp \leq 10^4$and $1 \leq Kd \leq 10^4$ has been chosen as replacement of former simulation parameters. Using proposed algorithm and$w_e = 10, \quad w_u = 0.5$, optimized parameters are calculated as Table 4.

History of these parameters in contrast to optimization iterations is displayed in Figure 11. Also, the cost function is demonstrated in Figure 12 which shows a smooth behavior after some iteration. The minimum cost is $J = 0.0914$.

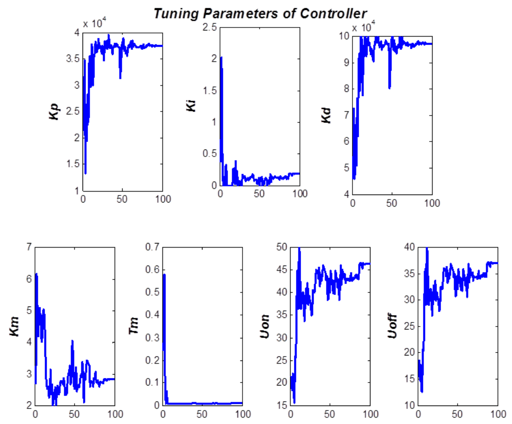

Fig. 11. Optimized parameters versus iterations for second system

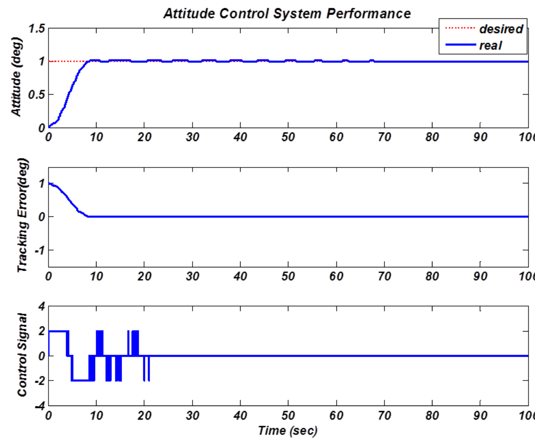

Fig. 13. Optimized controller performance for flexible spacecraft

Figure 13, discloses the controller performance simulated by acquired parameters. Command tracking by damping the significant flexible modes is evident. Also, both control signal and yaw output are comparable with designed controller in [2].

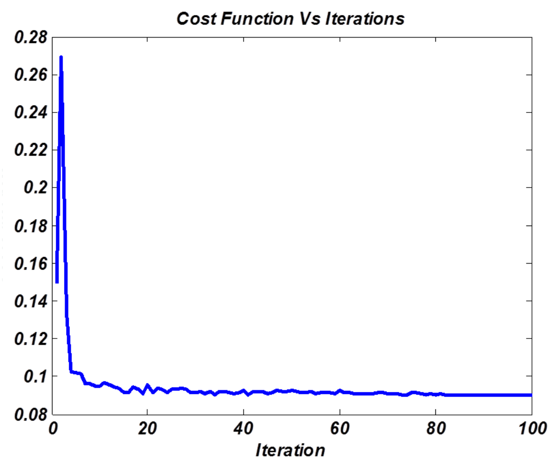

Fig. 12. Cost function versus iterations for third system

5 CONCLUSION

In this paper, a new methodology was presented for fine-tuning of PWPF-based spacecraft attitude controllers. Determining the changeable knobs of these controllers is an interesting topic in control science. This is as a result of the high degrees of freedom in the parameters and lack of rigorous linkages between them as well as relevant controller parameters. Many heuristic attempts have been made in the literature for fine-tuning of these controllers to achieve a good performance. Nevertheless, they all have trial-and-error nature without capability to give a general remedy. The proposed method uses advantages of particle swarm optimization to provide a general framework for tuning the PWPF-based controllers. This method has been simulated on PID-PWPF attitude controllers with various spacecraft dynamics. The executed simulation studies have justified the desirable applications and the obtained results are found to be promising.

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