Adaptive Force Control Using a Standard Deviation-based Hybrid Approach

Maethinee Songthai, Sarucha Yanyong, and Somyot Kaitwanidvilai

Abstract— **A good tracking response is essential for a force control system to achieve high performance in object handling. One of the significant challenges of the force control system is that the plant dynamics are directly dependent on the environment and the mechanical properties of the object. It's well-known that the mechanical properties of an object in manufacturing vary based on the type of product, gripper tools, and environment; hence, a non-adaptive controller may not be efficiently adopted. To address this issue, this paper proposes impedance control with hybrid adaptive algorithms to ensure the actuator system tracks the desired force command accurately. Particle Swarm Optimization (PSO) is adopted to adapt the impedance control parameters, thereby applying the capabilities of the learning system. A hybrid adaptive force control with a fitness function of the standard deviation and summation of error is proposed. The tracking response of the conventional adaptive controller was examined and compared with the proposed controller. The simulation results demonstrate the effectiveness of the proposed system.**

Index Terms— **force control, impedance control, hybrid controller, adaptive controller, and standard deviation**

I. INTRODUCTION

Nowadays, many applications in the manufacturing systems apply the force control to accomplish the tasks. Position control can be adopted for servo system; however, in several processes such as painting, pressing, attachment, etc., the performance of position control is not good enough. For example, in Hard Disk Drive (HDD) manufacturing, the using of position control for slider attachment process results in the blending of HDD suspension which is one of the most important defects in the manufacturing. It is well known that the dynamic of a force control system depends on the environment, mechanical properties of the handling object and gripper tools. Normally, the properties of environment and the object are time invariant system, which be varied and sometimes unknown. Thus, the dynamic model of the force control system is difficult to measure and often subjective. Generally, the design of force control can be categorized as two schemes those are direct force and indirect force controls. Direct force control can directly control the force by using the error from force reference and measured force from force/torque sensor.

The only force sensor is required for this control scheme. Indirect force control adopts both force and displacement sensors by assigning the position control as the inner loop and force control as the outer loop. One of the most popular indirect force controls is an impedance control which was invented by Hogan [1]. Parameters of the impedance controller consist of the specified mass (m), spring (k) and damper (b). Each parameter results in the overall mechanical properties of the entire system. For example, the damper can reduce the impact of contact force between the robot and the object. This benefit can prevent the damage caused by the impact force at the contact point. Many researches [2-4] applied the impedance controls to control the force control system. However, the environment of force control system is frequently changed and varied. Nonadaptive controls even impedance or force control is definitely not enough to deal with the system mentioned. Adaptive control can be applied to solve such problem. However, during the adaptation period, many adaptive controls do not produce the desired force response.

The undesired force response may cause the damage in the system when the adaptive controller is applied. Intelligent control such as Fuzzy control, Neural Network systems can be applied to the force control system. For the fuzzy control system, the human knowledge needs to be incorporated into the design and the knowledge from the expert is necessary for designing the control. Neural-network is one of the most adaptive techniques which adopt gradient method to solve problems. However, the undesired force response will be occurred at the learning period. In addition, Neural-network have the problem of local minima problem; thus, the initial weight and learning parameters need to be selected carefully. Unfortunately, the selection guideline of the parameters is not straight forward. Many optimizations can solve the problem of local minima such as Genetic algorithm, Particle swarm optimization, Searching Algorithm, etc. Among them, Particle swarm optimization [5] gained more attention since the programming of this method is not difficult and the particle can fly around the problem space for avoiding the local minima. Next iteration, the particle moves itself based on swarm movement to find the best solution. Although, the PSO is good for both programming and avoiding local minima problems, the learning period of this method is normally long. Besides, the undesired response of force appears in the system.

Thus, this paper proposes a new online adaptive force controller for controlling the impedance of the system. There are several research works related to the proposed system [6-8]. S. Kaitwanidvilai [6] applied the online adaptive

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controller to control the servo system. Genetic Algorithm is adopted for finding the optimal parameters of the control system. Undesired response is prevented by applying the hybrid bang-bang control. However, this technique is not easy to program. Rubaai A. and Jerry J. [7] applied the bang-bang controller with fuzzy system which are applied in the appliance industry. Hybrid adaptive model reference Neuro-fuzzy control was first proposed to control the internal force for pneumatic system by [8]. As result indicated, the proposed force control could be applied for controlling the unknown system dynamic. However, the Neuro-fuzzy adopted in such paper has the problem of local minima. To overcome such issues mentioned above, the PSO with hybrid bang-bang control is adopted in this paper for controlling the impedance of the entire system. The main problem of online adaptive controller is found in the learning period. At the learning period, the particle which is moved by PSO algorithm may be the worst solution which results in the undesired force response, damaging of the actuator and the environment. In this paper, impedance parameters of the controller are used as the particle of the PSO and the hybrid bang-bang is used for preventing the undesired force response. Impedance parameters are adequate for being as the adjusting parameters since all impedance parameters represent the behavior of the output response. For example, damping coefficient in the controller can reduce the overshoot or sudden change in the output response.

In the proposed control system, hybrid algorithm is utilized to switch controller modes between adaptive controller and bang-bang controller. When the magnitude of force error is higher than the specified threshold value, hybrid algorithm switches the controller from the adaptive control mode to bang-bang controller. The bang-bang controller, on-off controller, is a nonadaptive controller but gains high robustness. Although its performance is very poor performance; however, it can reduce the force error by moving the actuator in the opposite direction to avoid the damage. Fitness function in this paper is the combination of Integral square error (ISE) and Standard deviation (SD). ISE is adopted to force the output response to the desired response; while the SD is used to reduce the oscillation or overshoot at the learning period. The PSO is used to find the particle position which has the minimum fitness value. In this paper, simulation results verify that the proposed technique is applicable and the desired response is achieved.

II. IMPEDANCE CONTROL

Impedance control is a control method which defines the relation between the actuator and environment as the mechanical properties, i.e. mass, spring and damper. The desired impedance can be chosen in order that the desired output force response is achieved. Equations (1) and (2) represent the second order- mass-spring-damper system which is the ordinary impedance control.

$$G_{imp}(s) = \frac{1}{Ms^2 + Bs + K} \qquad (1)$$

$$G_{imp}(s) = \frac{x(s)}{F(s)} \qquad (2)$$

As shown in (1) and (2) show the selected impedance. In real operation, the impedance in (1) is used to convert the fore error $F(s)$ to the position $x(s)$ which is used as the reference command for the inner position control loop. The block diagram of impedance control is shown in Fig. 1. In this paper, PI is adopted as the inner loop controller for the position control loop.

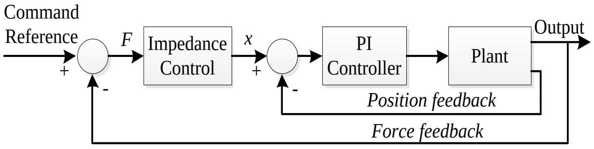

Fig. 1. Impedance control diagram

III. HYBRID IMPEDANCE CONTROL AND THE PROPOSED TECHNIQUE

The block diagram in Fig. 2 shows the proposed technique which PSO based impedance controller and Bang-bang controller can be used in hybrid fashion. The mode of operation is selected by the hybrid algorithm which considers the magnitude of force error as the decision parameter.

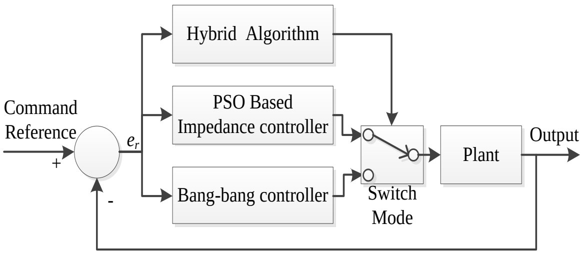

Fig. 2. Hybrid adaptive impedance controller.

Fig. 2 shows the hybrid adaptive impedance control which composes of PSO based impedance controller and the bang-bang controller. The PSO based impedance controller is The bang - bang controller is similar to the on-off control which can be simply expressed as the followings.

```
IF ( $e_r > e_{upper}$ )
THEN
        Bang-bang controller;
        $U = -V$;
ELSE IF ( $e_r < e_{lower}$ )
THEN
        Bang-bang controller;
        $U = +V$;
ELSE
        PSO based adaptive impedance controller;
END
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Where e_r is the force error; e_{upper} and e_{lower} are the upper and lower bounds of the force error threshold, respectively; U is the output signal and V is a maximum magnitude of the output signal.

IV. SIMULATION RESULTS

Normally, the bang-bang controller drives the actuator to opposite direction of the current movement. If the force error is in the range of the specified threshold value, the hybrid algorithm normally selects the PSO based adaptive impedance controller for adapting the impedance control. For more details of the PSO technique, the reader can find the details in [9]. In this paper, the fitness function is designed as the combination of Integral square error (*ISE*) and Standard deviation (*SD*).

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2 - \left(\frac{1}{N}\sum_{i=1}^{N} e_i\right)^2} \tag{3}$$

$$ISE = \sum_{i=1}^{N} e_i^2 \tag{4}$$

$$FITNESS = w_1 \cdot ISE + w_2 \cdot SD \tag{5}$$

Where w_1 and w_2 are the weight factors; e is the force error; N is the number of sampling.

V. SIMULATION RESULTS

This paper applied the proposed technique for controlling the PMDC (Permanent Magnet Direct Current motor) which is widely used in many kinds of application. The parameters of the DC motor adopted in this paper are shown in Table 1.
The transfer of PMDC motor can be written as:

$$G(s) = \frac{\theta(s)}{V(s)} = \frac{K_m}{s(JLs^2 + (JR + BL)s + BR + K_b)} \tag{6}$$

In this paper, we assumed that the environment of contact or the grasped object dynamic is spring. Thus, the force generated to the actuator can be written as (7):

$$F(s) = k \times \theta(s) \tag{7}$$

TABLE 1
PMDC MOTOR PARAMETERS

Parameter	Value
Resistance (R)	118.6Ω
Inductance (L)	$5.8\times10^{-9} H$
Torque constant (K_m)	$31.4\times10^{-3} N\cdot m/A$
Back emf constant (K_b)	$0.0314\ V/rad/s$
Viscous friction (B)	$0.1\times10^{-3} N\cdot m\cdot s$
Inertia (J)	$6.8\times10^{-8} kg\cdot m^2$

In this paper, we assumed the value of k as $1000kg/s^2$. Thus, the transfer function $G_f(s)$ can be written as (8):

$$G_f(s) = \frac{F(s)}{V(s)} = \frac{31.4}{3.944\times10^{-10}s^3 + 8.6448\times10^{-6}s^2 + 0.0433s} \tag{8}$$

The transfer function $G_f(s)$ is applied to plants of the simulation. The PSO parameters are selected as follows. Population size = 24, max velocity divisor = 2, acceleration constants = 2.1, inertia weights is [0.9:0.6], max iteration = 20 and the ranges of mass (m), spring (k) and damper (b) are [0.01:20] kg, [0.01:20] N/m and [1:700] $N\cdot s/m$. In this paper, PI controller is selected for the position control; parameters of the PI are selected as K_p = 28.5 and K_i = 7.

The output responses in Fig. 3 show the comparison between Non-Hybrid adaptive controller and Hybrid adaptive controller in the learning period. During this period, the particle in the PSO found the unwanted parameters, thus, undesired response will be appeared to the output response for both hybrid and non-hybrid controller. However, in the hybrid algorithm, the bang-bang control is applied when the magnitude of the force error exceeds the selected threshold values which are +2N and -2N for upper and lower bounds, respectively. As seen in the results, the hybrid algorithm change the controller to Bang-bang controller to drive the actuator avoiding the high overshoot response. In addition, Fig 4 shows the output response in the learned period. The high overshoot response is reduced by a hybrid algorithm which switch to bang-bang controller.

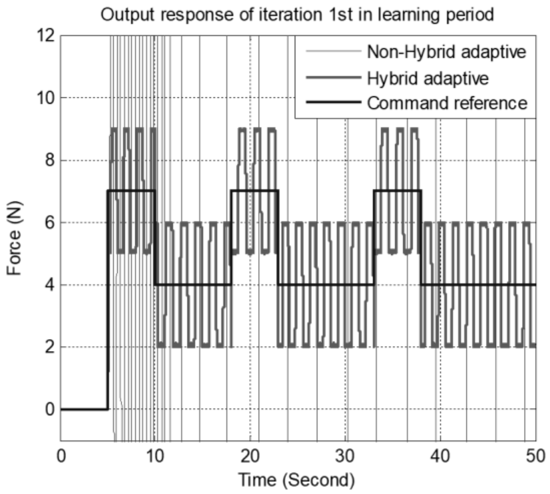

Fig 3. Output responses of Non-Hybrid and Hybrid adaptive controllers in learning period.

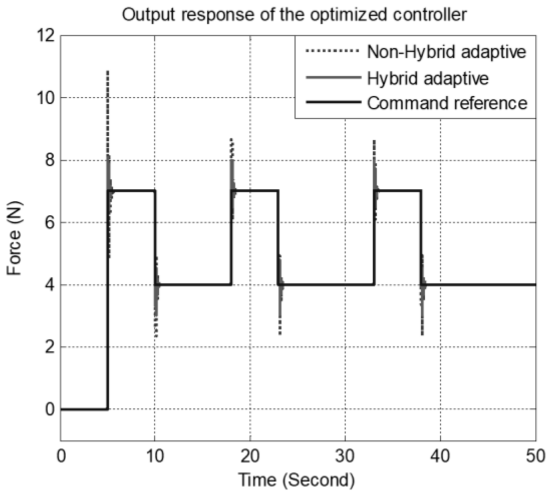

Fig 4. Output responses of Non-Hybrid and Hybrid adaptive controllers in the learned period

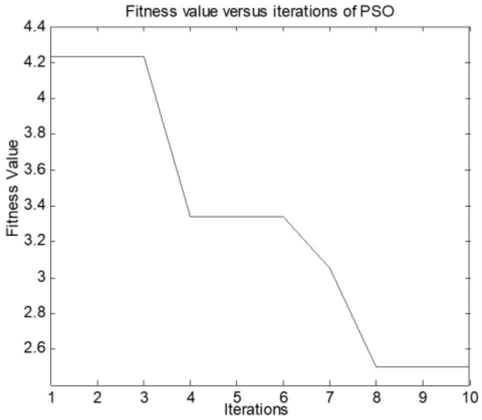

Fig 5. The convergence of the solution of the proposed controller

The output responses of the optimal impedance controller of non-hybrid and hybrid algorithms are similar. As seen in the results, the hybrid algorithm does not only prevent the system to avoid the unwanted response in learning period but also prevents the system from the overshoot and undershot over the specified lower and bounds. The optimization runs for 10 iterations to find the optimal value of impedance which the convergence of solution curve is shown in Fig. 5. The optimal values obtained by the PSO are mass=0.0100, spring=0.1000 and damper=9.263.

VI. CONCLUSION

he proposed hybrid algorithm improves the adaptive controller's ability to be used in online learning with the environment. The hybrid algorithm allows the adaptive controller to be utilized even when unwanted parameters are incorporated during the adaptation period, thereby preventing damage to the end-effector and environment. The hybrid algorithm effectively reduces overshoot and undershoot in the entire system by incorporating the standard deviation in the fitness function to minimize undesired oscillations, as demonstrated in the output response.

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