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WEIGHT OPTIMIZATION AND STRUCTURE-SPECIFIED ROBUST H_∞ LOOP-SHAPING CONTROL OF A PNEUMATIC SERVO SYSTEM USING GENETIC ALGORITHM

S. Kaitwanidvilai,^{*,**} P. Olanthichachai,^{*} and I. Ngamroo^{*}

Abstract

H_∞ loop-shaping (HLS) is a feasible method for designing a robust controller; however, the controller designed by this method is usually complicated with high order. To overcome this problem, we propose a new design technique, weight selection and structure-specified HLS control using genetic algorithms (GAs), to design a robust controller. In the proposed technique, both the performance weight and structures-specified robust loop-shaping controller are simultaneously determined by GA. The performance and robust stability conditions of the designed system satisfying the HLS are formulated as the objective function in the optimization problem. The designed controller contains simple structure with lower order and still retains the robustness and performance specification. As shown in the simulation results, the robustness and performance of the proposed controller are almost identical to those of the controller designed by HLS method and the proposed technique leads to performance comparable to that of the reduced-order controller. Experiments on the pneumatic actuators of a pneumatically actuated robot are performed to verify the effectiveness of the proposed technique.

Key Words

H_∞ loop-shaping control, robust control, pneumatic robot, pneumatic actuator

1. Introduction

In the past decades, many developments in pneumatic controllers have been done and the results of those are extensively used in today's industrial processes. Pneumatic ac-

tuator is an attractive choice for being used in both industrial and non-industrial applications because of the following advantages – high reliability, mainly because of fewer moving parts; self-cooling; high power-to-weight ratio; easy installation and maintenance; and the availability of a wide range of standard sizes. Recently, this actuator has been used in the designing of the robot manipulators to enhance capabilities of the robot. Because of the advantages of this actuator, pneumatic robot is now an attractive choice for the industrial robot. In a pneumatic system, normally, the piston can stop only at two-end terminal points. To extend the capabilities of the system, this research is conducted to develop a control algorithm for a pneumatic robot arm. Position of the pneumatic piston in each link of the robot is controlled in such a way that the controlled piston can move to any target position.

Pneumatic system is highly nonlinear because of its compressibility of air and highly nonlinear flow through pneumatic components. Furthermore, in a long connecting tube, the effects of time delay are significant. These lead to a difficulty in analysing and designing an effective controller for the system. Many researchers investigated various control techniques to control the system. Several approaches based on nonlinear control techniques have been successfully applied to design a controller for pneumatic system, such as block-oriented approximate feedback linearization by Xiang and Wikander in 2003 [1], fuzzy state feedback control by Schulte and Hahn in 2004 [2], etc. Unfortunately, because of time consuming in system identification process and many feedback states, these techniques are now only implemented in very precise requirement applications but not in general industrial applications.

In linear control point of view, linear model is derived from linear mathematic equations. Mostly, linear dynamic model is obtained by applying the linearization technique around a specified operation point, usually at the middle of pneumatic cylinder. Various control techniques based on linear control have been proposed to control a pneumatic system such as simple proportional integral derivative (PID) control [3], proportional integral (PI) control with analog loop [4], self-tuning control [5], etc. As these

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techniques do not include the presence of system uncertainties, robustness in the sense of uncertainties of these designed controllers cannot be guaranteed. To solve this problem, some researchers applied the robust control of a pneumatic system. Kimura *et al.* [6] proposed the H_∞ control with mirror feedback for a pneumatic actuator system. Inner pressure loop is used to reduce the complexity of resulting controller in H_∞ control. Kimura *et al.* [7] also applied a sampled-data H_∞ control approach into the plant. Experimental results in their work showed the advantages of discrete H_∞ control over the continuous H_∞ control in certain senses.

Several techniques to design an effective controller were proposed in [8–11]. An adaptive switching learning control method for trajectory tracking of robot manipulators was proposed in [8]. In this paper, the off-line learning off-sets the difficulty of control with one complicated controller such as sliding mode controller. In some techniques such as robust H_∞ optimal control, the structure of controllers is complicated with a high order. It is difficult to implement these controllers in practise. Currently, structure-specified controller becomes an interesting area of research because of their simple structure and acceptable controller order. In this technique, the structure of controller is first specified and then the controller parameters are evaluated. The integrated design of mechanical structure and control algorithm for a programmable four-bar linkage was proposed in [9]. In this paper, the optimization technique is used to determine the controller parameters (gains of the proportional derivative (PD)) as well as the parameters of the plant structure [9]. The approaches to design a robust control for structure-specified controller were proposed in [10, 11]. In [10], a robust H_∞ optimal control problem with structure-specified controller was solved by using genetic algorithm (GA). Chen *et al.* [11], proposed a PID design algorithm for mixed H_2/H_∞ control. In their paper, PID controller parameters were tuned in the stability domain to achieve mixed H_2/H_∞ optimal control.

A difficulty with the H_∞ optimal control approach is that the appropriate selection of closed-loop objectives and weights is not straightforward. Alternatively, robust controller can be designed by using H_∞ loop-shaping (HLS) control [12] which is a simple and efficient technique for designing a robust controller. Uncertainties in this approach are modelled as normalized co-prime factors. This technique requires only two specified weights, pre- and post-compensator weights, for shaping the nominal plant so that the desired open-loop shape is achieved. Fortunately, the selection of such weights is based on the concept of classical loop-shaping which is a well-known technique in the controller design. By the reasons mentioned earlier, this technique is simpler and more intuitive than other robust control techniques. However, the controller designed by HLS is still complicated. The selection of weights in the design for achieving both time domain and frequency domain specifications is not easy. To overcome these problems, in this paper, GA-based *Weight Optimization and Structure-Specified* HLS control is proposed to design a pneumatic controller. In this paper, we propose a GA to evaluate an appropriate performance weight W_1 satisfy-

ing the performance specifications and robustness. This then reduces the difficulty in selecting appropriate weight in HLS control. The controller designed by the proposed approach has a good performance and robustness as well as simple structure. This allows our designed controller to be implemented practically and reduces the gap between the theoretical and practical approach.

The remainder of this paper is organized as follows. Pneumatic actuator and pneumatic robot dynamics are described in section 2. Conventional HLS and the proposed technique are discussed in section 3. Section 4 demonstrates the design example and results. And, finally, in section 5 the paper is summarized with some final remarks.

2. Dynamic Model

In this research work, we constructed a cylindrical type robot arm with pneumatic actuators. This robot is widely used in many industrial processes. Consider the cylindrical type robot arm shown in Fig. 1, it is seen that it consists of two translation joints and a revolute joint. Generally, the dynamic model of this robot can be written as [13]:

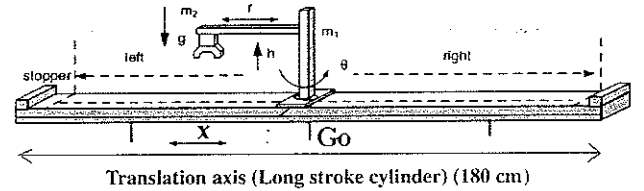


Figure 1. A cylindrical robot arm.

$$\begin{bmatrix} J + m_2 r^2 & 0 & 0 \\ 0 & m_1 + m_2 & 0 \\ 0 & 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{h} \\ \ddot{r} \end{bmatrix} + \begin{bmatrix} 2m_2 r \dot{r} \dot{\theta} \\ 0 \\ -m_2 \dot{\theta}^2 \end{bmatrix} + \begin{bmatrix} 0 \\ (m_1 + m_2)gh \\ 0 \end{bmatrix} = \begin{bmatrix} n_1 \\ f_2 \\ f_3 \end{bmatrix}$$

$$\tau = [n_1 \ f_2 \ f_3]^T \quad (1)$$

where m_1 and m_2 are the mass of the vertical and horizontal links, respectively; θ is the angle of the rotation axis; g is the gravity; J is the inertia of the base link; h is the distance of the vertical link; r is the distance of the horizontal link; x is the distance of the translation axis; τ is the force vector; and n_1 , f_2 , and f_3 are the torque in rotation axis, force in vertical and horizontal axis, respectively.

The dynamic model in (1) is derived from the Lagrange's equations of motion [13, 14] and can be applied indirectly to describe the dynamic model of our developed robot. The model of translation axis can be treated as the actuator model as shown in (2). There are many control schemes to control a robot manipulators such as computed torque control, independent joint control, etc. In computed torque control, the control design problem is decomposed

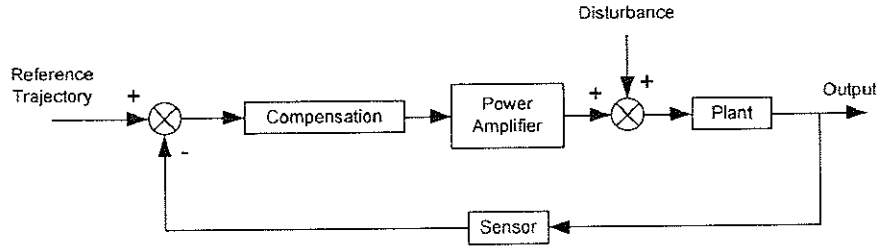


Figure 2. Independent joint control scheme.

into an inner loop design and an outer loop design. The nonlinear inner loop is used to compute the inverse dynamic of the robot for cancelling the nonlinear term while the outer loop control is used for trajectory tracking. In the industrial robotic applications, *independent joint control* is widely used because it allows a decoupled analysis of the closed-loop system. At present, it is strongly accepted by several researchers that this kind of control scheme is more practically suitable for implementing in industrial robotic applications because the nonlinear control schemes used in the computed torque control scheme is too complicated to be utilized in practise. In this control scheme, each axis of the manipulators is controlled as a SISO system. Any coupling effects due to the motion of the other links are treated as disturbances. Figure 2 shows the diagram of the independent joint control scheme. A picture of developed robot in this paper is shown in Fig. 3. Based on this control scheme, in this paper, the position of piston in each actuator of the robot is controlled separately. In pneumatic robot, the actuator dynamics is very crucial. The foundation research works on modelling of a servo pneumatic system were derived by the study of relationship of gas properties and motion's equation in pneumatic cylinder. Linear dynamic model of a pneumatic actuator can be written as [15, 16]:

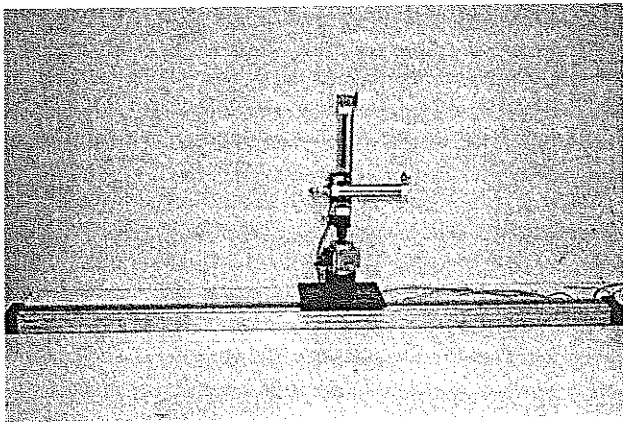


Figure 3. A pneumatically actuated robot.

$$G(s) = \frac{y(s)}{u(s)} = \frac{k_1}{s(s^2 + \frac{C}{M}s + k_2)} \quad (2)$$

Where $k_1 = \frac{\gamma RTG}{M} \left(\frac{A}{V_{1o}} + \frac{A}{V_{2o}} \right)$, $k_2 = \frac{\gamma}{M} \left(\frac{A^2 P_{1,o}}{V_{1o}} + \frac{A^2 P_{2,o}}{V_{2o}} \right)$, $y(s)$ is the position output, $u(s)$ is the valve's input voltage, A is the bore area, G is the coefficient of the linearized

air mass flow rate, C is the viscous friction coefficient, γ is the ratio of specific heat = 1.4, V_{io} is the air's volume in the chamber i at nominal position, M is the total load mass, $P_{i,o}$ is the pressure in the chamber i , o is a subscript denoting the operation point, T is the air temperature (K) and R is the gas constant = 29.2 m/K.

As seen in (2), the dynamic model of servo pneumatic is modelled as a third-order transfer function. This model is frequently used in the design of linear controller for a pneumatic servo system. To identify this model, some authors directly evaluated model's parameters by measuring the physical parameters [15, 16]. Alternatively, identification method by evaluating the optimal model parameters to minimize the least square of prediction error can be used to identify the linear model [17].

In this paper, the standard system identification for identifying the robot dynamics is applied. Based on the concept of independent joint control scheme, the dynamic model of each axis of the robot is identified separately. The details of system identification of the developed robot are illustrated in Section 4.

3. HLS Control and Proposed Technique

This section illustrates the concepts of the conventional HLS control and the proposed technique.

3.1 Conventional HLS

HLS control proposed by McFarlane and Glover [12] is an efficient method to design a robust controller. This approach requires two weighting functions, W_1 (pre-compensator) and W_2 (post-compensator), for shaping the original plant G_0 so that the desired open-loop shape is achieved. In this approach, the shaped plant is formulated as normalized co-prime factor, which separates the shaped plant G_s into normalized nominator N_s and denominator M_s factors [18]. Note that, $G_s = W_2 G_0 W_1 = N_s M_s^{-1}$.

The following steps can be applied to design the HLS controller:

Step 1. Shape the singular values of the nominal plant G_0 by using a pre-compensator W_1 and/or a post-compensator W_2 to get the desired loop shape. In SISO system, the weighting functions W_1 and W_2 can be chosen as:

$$W_1 = K_w \frac{s + \alpha}{s + \delta} \text{ and } W_2 = 1 \quad (3)$$

where K_w , α , and δ are positive values. δ is typically chosen as a small number ($\ll 1$) for an integral action.

W_2 can be chosen as a constant because the effect of the sensor noise is negligible when the use of good sensor is assumed [19]. If the shaped plant $G_s = N_s M_s^{-1}$, the perturbed plant is written as:

$$G_\Delta = (N_s + \Delta_{N_s})(M_s + \Delta_{M_s})^{-1} \quad (4)$$

where Δ_{N_s} and Δ_{M_s} are stable, unknown representing the uncertainty satisfying, $\|\Delta_{N_s}, \Delta_{M_s}\|_\infty \leq \varepsilon$, ε is the uncertainty boundary called stability margin. There are some guidelines for selecting the weight available in [19].

Step 2. Calculate ε_{opt} , where:

$$\varepsilon_{opt} = \left(\inf_{K \text{ stabilizing}} \left\| \begin{bmatrix} I \\ K \end{bmatrix} (I + G_s K)^{-1} M_s^{-1} \right\|_\infty \right)^{-1} \quad (5)$$

To determine ε_{opt} , there is a unique method explained in [19]. $\varepsilon_{opt} \ll 1$ indicates that W_1 or W_2 designed in *Step 1* are incompatible with robust stability requirement. To ensure the robust stability of the nominal plant, the weighting function is selected so that ε_{opt} is large enough [19]. If ε_{opt} is not satisfied, then go to *Step 1*, adjust the weighting function.

Step 3. Select $\varepsilon < \varepsilon_{opt}$ and then synthesize a controller K_∞ that satisfies:

$$\left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M_s^{-1} \right\|_\infty \leq \varepsilon^{-1} \quad (6)$$

Controller K_∞ is obtained by solving the sub-optimal control problem in (6). The details of this solving are available in [18]. To determine M_s , there is a method explained in [19].

Step 4. Final controller (K) is determined as follows:

$$K = W_1 K_\infty W_2 \quad (7)$$

Figure 4 shows the controller in HLS.

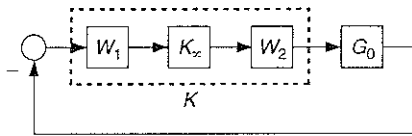


Figure 4. HLS design.

3.2 GA-based Weight Optimization and Structure-Specified HLS Optimization

In the proposed technique, GA is adopted in both weight selection and control synthesis. GA is well known as an algorithm that can be applied to any optimization problem. This algorithm applies the concept of chromosomes, and the genetic operations of crossover, mutation and reproduction. At each step, called generation, fitness value of each chromosome in population is evaluated by using fitness function. Chromosome, which has the maximum

fitness value, is kept as a solution in the current generation and copied to the next generation. The new population of the next generation is obtained by performing the genetic operators such as crossover, mutation and reproduction. In this paper, a roulette wheel method is used for chromosome selection. In this method, chromosome with high fitness value has high chance to be selected. Operation type selection, mutation, reproduction or crossover depends on the pre-specified operation's probability. Normally, chromosome in genetic population is coded as binary number. However, for the real number problem, decoding binary number to floating number is applied [20]. The proposed technique is described as follows.

Weight selection is an important procedure for HLS. Some researchers incorporated the performance specifications for selecting the appropriated weights [21, 22]. Based on (6), ε can be used for indicating the robust performance of the designed controller. In the proposed technique, we adopt this margin as the objective function. Although the proposed controller is structured; however, it still retains the entire robustness and performance guarantee as long as a satisfactory uncertainty boundary ε is achieved.

In our technique, the predefined structure controller is denoted as $K(p)$, the performance weighting function is denoted as $W_1(x)$, p and x are the control parameters in $K(p)$ and weight parameters in $W_1(x)$, respectively. Based on the concept of HLS, optimization goal is to find the parameters p in the controller $K(p)$ and the parameters x in the weighting function $W_1(x)$ that minimize infinity norm from disturbances w to states z , $\|T_{zw}\|_\infty$.

In the proposed technique, the final controller K is defined as:

$$K = K(p)W_2 \quad (8)$$

Assuming that W_1 is invertible, from (7) then it is obtained that:

$$K_\infty = W_1^{-1}K(p) \quad (9)$$

In many cases, the weight W_2 is selected as identity matrix I . However, if W_2 is a transfer function matrix, then the final controller is the controller $K(p)$ in series with the weight W_2 . By substituting (9) into (6), the ∞ -norm of the transfer function matrix from disturbances to states, $\|T_{zw}\|_\infty$, which is subjected to be minimized can be written as:

$$J_{cost} = \gamma = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}(x)K(p) \end{bmatrix} (I + G_s W_1^{-1}(x)K(p))^{-1} M_s^{-1} \right\|_\infty \quad (10)$$

To incorporate the performance into the optimization problem, time domain and frequency domain specifications are considered. Rather than minimizing some objective functions, it is more naturally to define the performance specifications for control system design in terms of algebraic or functional inequalities. For example, in the step

response, the system may be required to have a rise-time less than 0.4 s, a settling time less than 1 s and an overshoot less than 5%. Consequently, the performance specifications are adopted as constraints in the design problem. The optimization problem can be written as:

$$\begin{aligned} \text{Maximize } & \left\| \begin{bmatrix} I \\ W_1^{-1}(x)K(p) \end{bmatrix} (I + G_s W_1^{-1}(x)K(p))^{-1} M_s^{-1} \right\|_{\infty}^{-1} \quad (11) \end{aligned}$$

$$\begin{aligned} \text{Subject to } & p_{i,\min} < p_i < p_{i,\max}, \\ & x_{i,\min} < x_i < x_{i,\max}, \end{aligned}$$

$$\left. \begin{aligned} \text{Maximum Overshoot} &< OV \\ \text{Settling Time} &< ST \\ \text{Steady-State Error} &< SE \end{aligned} \right\} \text{(Constraints in time domain)}$$

$$\left. \begin{aligned} \text{Bandwidth} &> BW \\ \text{Gain}(\omega < \omega_{\text{low freq}}) &> LG \end{aligned} \right\} \text{(Constraints in frequency domain)}$$

where OV is acceptable maximum overshoot; ST is acceptable settling time; SE is acceptable steady-state error; and BW is bandwidth of the desired loop shape.

where $p_{i,\min}$, $x_{i,\min}$ and $p_{i,\max}$, $x_{i,\max}$ are the lower and upper bound values of the parameter p_i and x_i in the parameter vector p and x , respectively. Some methods for selecting the range of parameter are shown in [10, 11]. OV , ST , SE , BW , LG , and $\omega_{\text{low freq}}$ are specified values. ω is frequency. The term "Gain($\omega < \omega_{\text{low freq}}$)" is defined for good performance in some frequency range, typically some low frequency ($\omega \in [0, f_{\text{req}}]$). Other specifications can be added to achieve additional specifications. All constraints mentioned earlier are selected based on the actuator bandwidth and design specifications. The fitness function in the controller synthesis can be written as:

$$\begin{aligned} \text{Fitness (J)} &= \begin{cases} \left(\left\| \begin{bmatrix} I \\ W_1^{-1}(x)K(p) \end{bmatrix} (I + G_s W_1^{-1}(x)K(p))^{-1} M_s^{-1} \right\|_{\infty} \right)^{-1} & \text{if the constraints are met} \\ 0.01 & \text{otherwise} \end{cases} \quad (12) \end{aligned}$$

The fitness is set to a small value (in this case is 0.01) if the constraints are not met. Our proposed algorithm is summarized as follows:

Step 1. Specify controller structure $K(p)$, weighting function structure $W_1(x)$ and the control and weighting function parameter ranges. Define the genetic parameters such

as population size, crossover and mutation probability, maximum generation, etc. Also, specify the performance specifications such as OV , ST , SE , etc.

Step 2. Initialize several sets of parameters p and x in the 1st generation. In this case, each $[p, x]$ is a chromosome.

Step 3. Evaluate the fitness value of each chromosome using (12). Select the chromosome with maximum fitness value as a solution in the current generation. Increment the generation for a step.

Step 4. While the current generation is less than the maximum generation, create a new population using genetic operators and go to **Step 3**. If the current generation is the maximum generation, then go to **Step 5**.

Step 5. Check performances in both frequency and time domains. If the performance is not satisfied such as too low ε (too low fitness function), then go to **Step 1** to change the structure of controller or the weight. Low ε indicates that the selected structure is not suitable for the problem.

4. Simulation and Experimental Results

The proposed technique is applied to design a controller of a 4-axis pneumatic robot. This section explains the design of controller for the translation axis and controllers in the other axes are designed by the same design procedure. In this paper, the standard system identification using experimental data is applied to determine the dynamic model of a pneumatic robot. Based on the concept of the independent joint control scheme, the dynamic model of each axis of the robot must be identified separately. The appropriate input valve voltage signal, pseudo binary random signal (PBRs), is applied to the actuator in the axis attempted to be identified, while the pistons of actuators in other axes are maintained at the nominal positions. The estimated model is obtained when the difference between model's output, prediction and the measured output data is minimized [17]. In this paper, an appropriate input signal was applied to the actuator in translation axis. The data from valve's voltage input and position output are collected and used for the system identification. Simple black-box system identification was used in our work. In this approach, the structure and parameters of the plant are assumed to be unknown. Firstly, a model is selected from the standard models such as *ARMAX*, *ARX*, *OE*, etc. Then, the orders of pole, zero, delay and so on in the model are selected and the system identification using prediction method is applied [17]. The appropriate dynamic model can be obtained by adjusting these orders or changing the model. These processes are done by trial and error. In this paper, to identify the plant's parameters, *OE (output error) model* is selected. The details of the standard system identification and *OE model* are available in [17]. Units of output and input are metre and volt, respectively. In our experiments, long pneumatic hoses which can be modelled as the input time delay are used. Sampling time in our control system is 0.0112 s and the delay time of about 0.11 s is measured. The time delay is realized in the plant transfer function by its second-order Pade approximation. From the procedure discussed previously, the identified plant model is found to be:

$$G_0 = \frac{0.032s^2 + 3.125s + 2.811}{s^3 + 12.82s^2 + 10.55s + 0.4715} e^{-0.11s} \quad (13)$$

$$\approx \frac{0.032s^4 + 1.349s^3 - 135.4s^2 + 2946s + 2788}{s^5 + 67.37s^4 + 1702s^3 + 13290s^2 + 10490s + 467.6}$$

Note that, this identified model includes the dynamics of actuator, pneumatic pipe, valve, A/D, mass of the other links, etc. The comparison of the simulated model output and the measured output is shown in Fig. 5. The results show that the plant model is accurately approximated by the identified model.

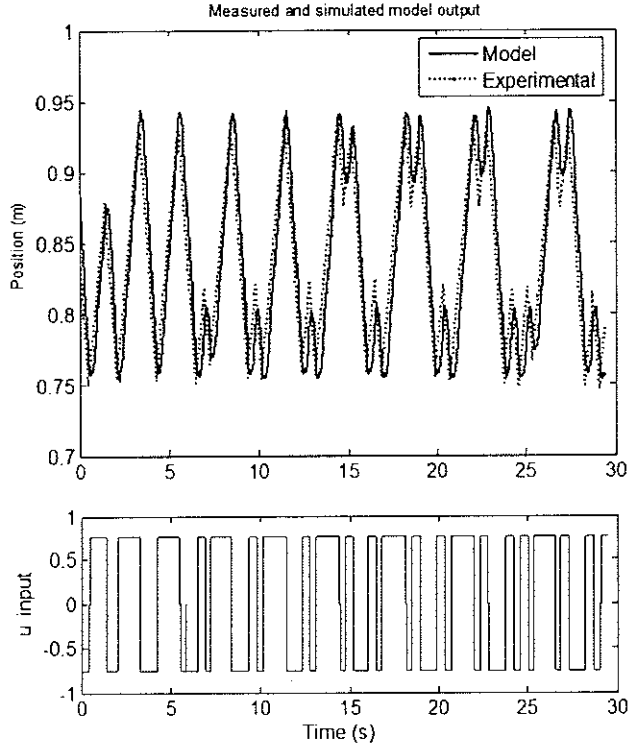


Figure 5. Comparison between simulated and measured outputs.

Next, a structure-specified robust controller using the proposed algorithms is designed. The structure of controller is selected as PID with first-order derivative filter. The controller structure is expressed in (14). K_p , K_i , K_d , and τ_d are parameters to be evaluated. In this paper, weighting function (W_1) are selected as (15). x_1 and x_2 are parameters that will be evaluated:

$$K(p) = K_p + \frac{K_i}{s} + \frac{K_d s}{\tau_d s + 1} \quad (14)$$

$$W_1(x) = \frac{x_1 s + x_2}{s + 0.001} \quad (15)$$

Based on (15), the weight parameters ranges is selected as $x_1 \in [0.01, 50]$, $x_2 \in [0.01, 50]$. The performance specification in (9) is selected as $OV=0.05$, $SE=0.005$, $ST=1.2s$, $BW=3.5 \text{ rad/s}$, $\omega_l=0.1 \text{ rad/s}$, $G_u=20 \text{ dB}$. In the optimization, the ranges of search parameters and

GA parameters are set as follows: $K_p, K_i, K_d \in [0.01, 100]$, $\tau_d \in [0.01, 10]$, population size=200, crossover probability=0.7, mutation probability=0.2 and maximum generation=25. As a result, the optimal controller and weighting function are found to be:

$$(PPID)K^*(p) = 8.966 + \frac{0.2986}{s} + \frac{0.0982s}{0.0732s + 1} \quad (16)$$

$$W_1 = \frac{13.514s + 0.3321}{s + 0.001} \quad (17)$$

Based on (3), $W_2=1$. In our simulation work, we use Pentium IV-1GHz computer, with 512MB SDRAM. In our design, MATLAB program, Genetic Algorithm Toolbox and Robust Control toolbox [23] are used to develop the computer code. It took only 38 min to converge the solution. Figure 6 shows a plot of convergence of fitness function (optimal stability margin) versus generations by GA. After the 14th generation, the optimal solution is obtained. As shown in the figure, the optimal robust PID-type-structured-controller provides a satisfied stability margin at 0.4903. In the proposed technique, stability margin is used to indicate the robust performance of the designed system. In addition, the convergence of controller and weight parameters is shown in Fig. 7.

With the designed weighting functions, the crossover frequency of the desired system is increased to 4 rad/s. Specified time domain specifications of the system are met. Bode plots of open-loop transfer function for the nominal plant and shaped plant are shown in Fig. 8. As shown in this figure, at low frequency, the open-loop gain of shaped plant is much larger than that of the nominal plant. This makes the designed system good in terms of performance tracking and disturbance rejection. In this case, the shaped plant is then determined as:

$$G_s = W_1 G_0 W_2 = \frac{13.514s + 0.3321}{s + 0.001} \cdot \frac{0.032s^4 + 1.349s^3 - 135.4s^2 + 2946s + 2788}{s^5 + 67.37s^4 + 1702s^3 + 13290s^2 + 10490s + 467.6} \quad (18)$$

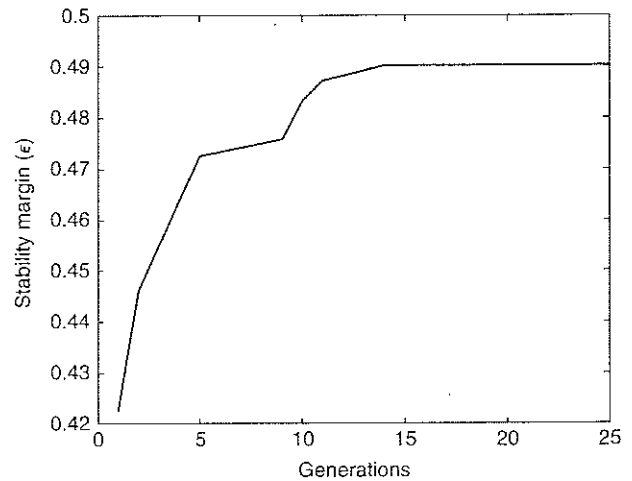


Figure 6. Convergence of the fitness value.

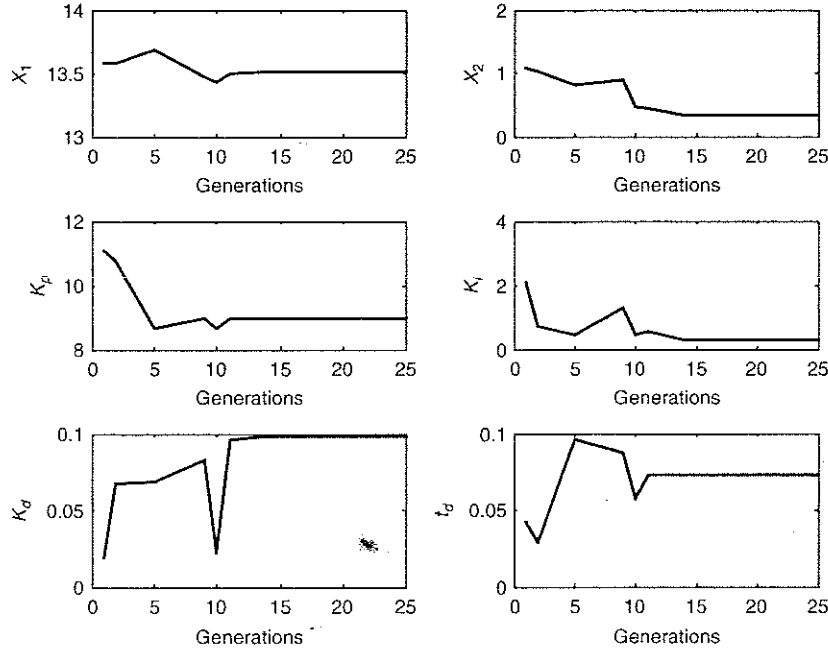


Figure 7. Convergence of the controller and weight parameters.

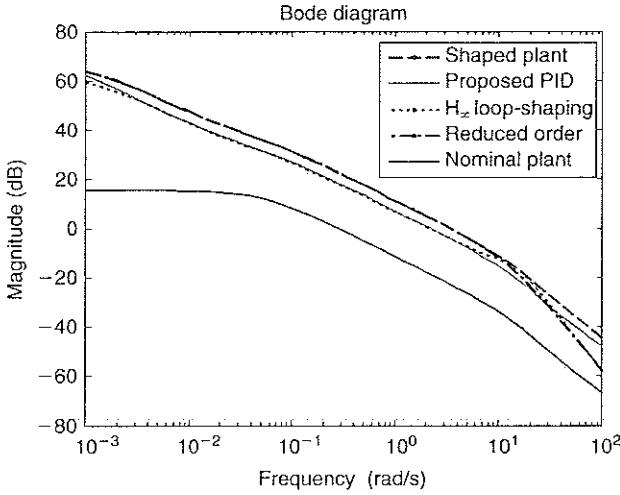


Figure 8. Bode diagram of the open-loop transfer function for: the shaped plant, nominal plant, plant with HLS, reduced-order controller, and proposed controller.

To evaluate the performance and robustness of the proposed system, responses of the system from conventional HLS, proposed robust PID-type-structured-controller (PPID), PID tuned by Ziegler-Nichols method (ZN), PID tuned by Tyreus-Luyben rule (TLC) and reduced-order controller are investigated. We first design a controller by the conventional HLS procedure by using the weighting function in (17). By this weight, ε_{opt} is found to be 0.554 and ε is set to be 0.503, which is less than the optimal value. Then, the HLS controller (the full-order controller) can be evaluated as follows:

$$K(s) = W_1 K_\infty W_2 = \frac{13.514s + 0.3321}{s + 0.001} \quad (19)$$

$$\left(\frac{21.15s^5 + 1429s^4 + 36210s^3 + 285500s^2 + 230200s + 5554}{s^6 + 85.66s^5 + 3013s^4 + 50110s^3 + 465000s^2 + 393100s + 9382} \right)$$

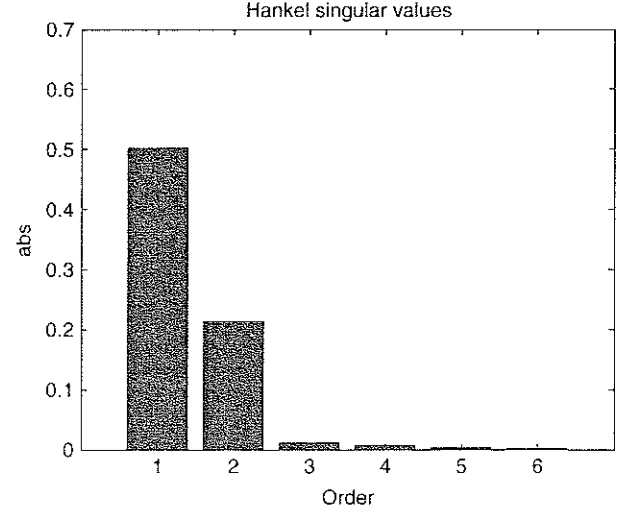


Figure 9. Hankel singular values distribution of the full-order controller.

As shown in (19), the controller designed by HLS controller is seventh-order controller and complicated. It is not easy to implement practically. Generally, the reduced-order controller can be designed by the Hankel norm model reduction. This technique determines an appropriate reduced order by plotting the Hankel singular values of the full-order controller to determine which modes (states) can be discarded without sacrificing the key characteristics [23]. Figure 9 shows the plot of Hankel singular values of the resulting controller. As seen in this figure, there are two dominant modes in the controller. Thus, the second-order reduced-order controller can be designed as follows:

$$K_r(s) = \left(\frac{294.8s + 8.014}{s^2 + 21.44s + 0.002144} \right) \quad (20)$$

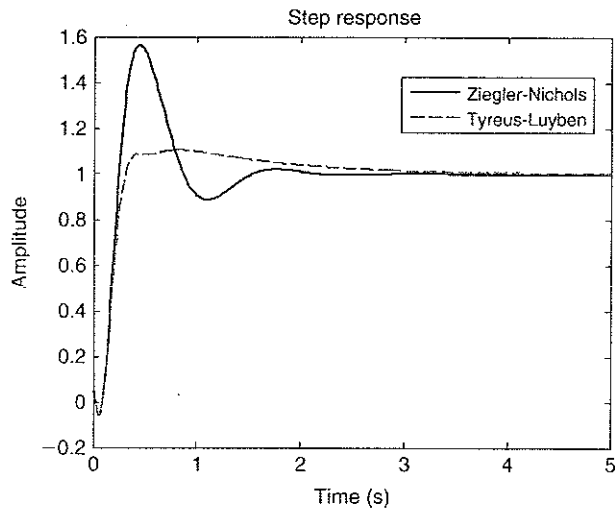


Figure 10. Responses from the PID controller tuned by ZN and TLC tuning rules.

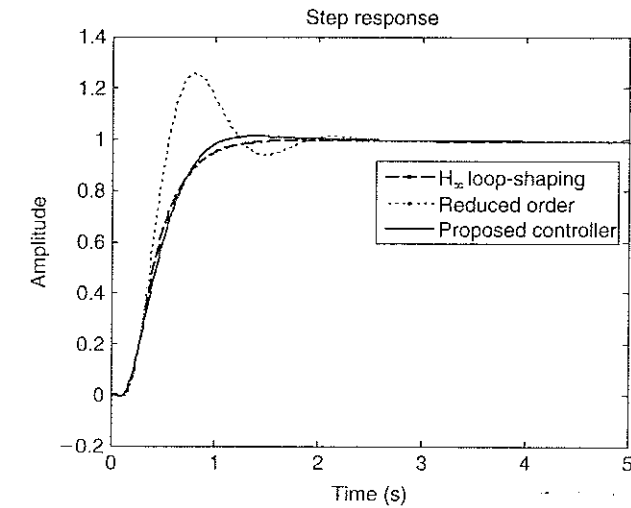
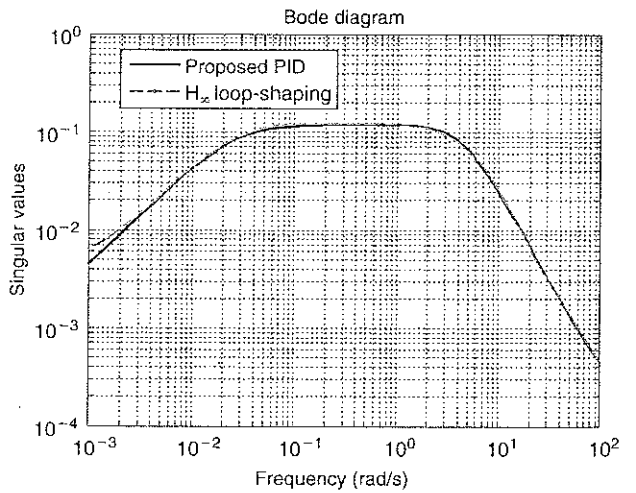
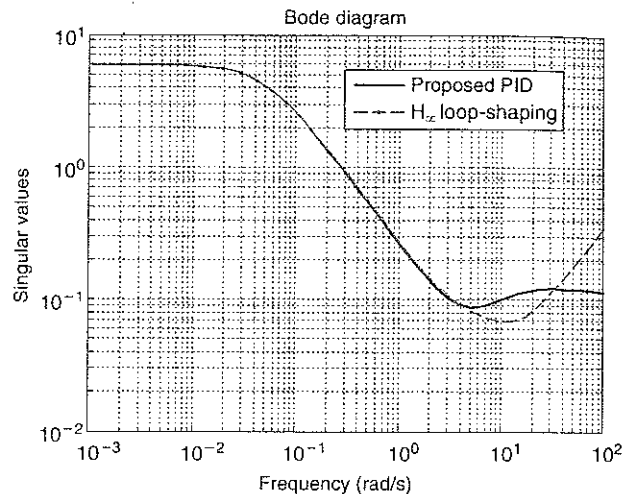
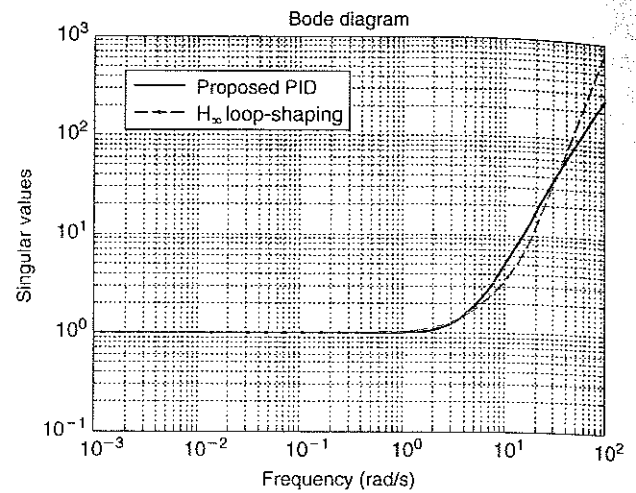


Figure 11. Step responses by the HLS, reduced-order controller and proposed PID.

The stability margin obtained from this controller is only 0.3007. Clearly, the stability margin of our proposed controller is much better than that of the reduced-order controller. Open-loop bode diagram is plotted to verify the proposed algorithm. Figure 8 shows comparison of the plant, the shaped plant, the loop shape by the proposed controller, reduced-order controller and HLS. As shown in this figure, all loop shapes by the proposed controller, reduced-order controller and HLS are close to the desired loop shape.

Additionally, for performance comparison, PID tuned by ZN and PID tuned by TLC are also designed. Both tuning rules do not require an analytic model of the plant. These methods are widely used for PID tuning in many kinds of systems. In these methods, gains K_p , K_i , and K_d are tuned using the ultimate gain, K_u , and ultimate period, T_u . To evaluate K_u and P_u , the integral and derivative gains in PID controllers are set to zero. Ultimate gain, K_u ,

Figure 12. (a) Maximum allowable multiplicative plant perturbation, $1/\bar{\sigma}(GK(I + GK)^{-1})$; (b) maximum allowable additive plant perturbation for closed-loop stability, $1/\bar{\sigma}(K(I + GK)^{-1})$; and (c) gain from input disturbance to plant output, $\bar{\sigma}((I + GK)^{-1}G)$.

is the proportional gain value that results in a sustained periodic oscillation in the output. Ultimate period, P_u , is the period of oscillation. The details of tuning by ZN and TLC are given in [24]. Responses of the unit step

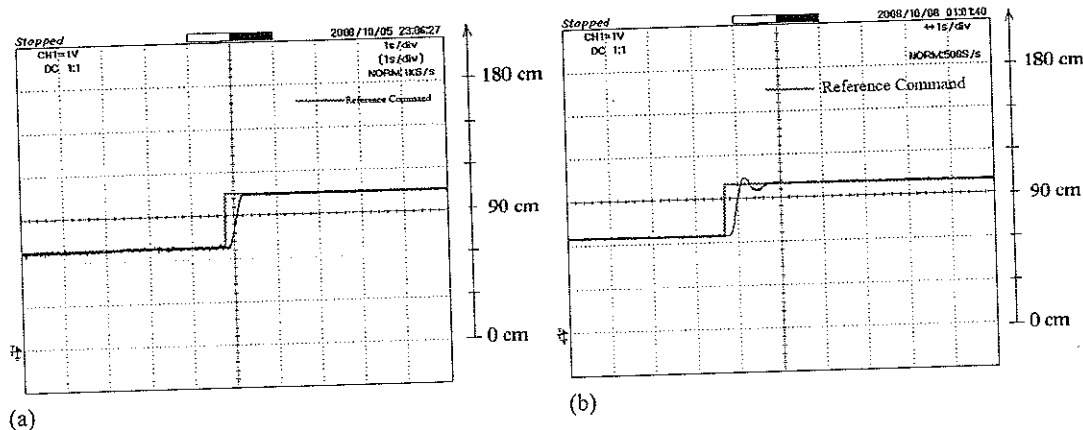


Figure 14. Response by (a) the proposed controller and (b) reduced-order controller in translation axis.

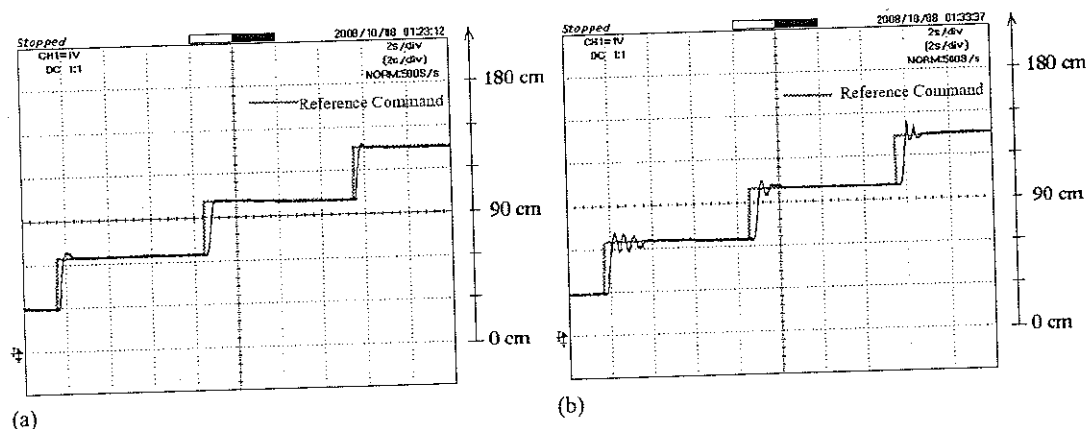


Figure 15. Response by (a) the proposed controller and (b) reduced-order controller in the translation axis when the ladder input command is applied and supply pressure is changed to 600 kPa.

small difference in the maximum overshoot. The experimental results show that the proposed controller has good robust performance from the changing of operating pressure and operating point. The reduced-order controller is also applied to control this perturbed plant and the result is shown in Fig. 15(b). As shown in this figure, oscillations and overshoot in the response are much increased.

5. Conclusions

In this paper, the appropriated performance weight W_1 and controller satisfying the time domain and frequency domain specifications and robustness are evaluated by GA. As shown in the simulation results, the responses from the proposed controller and HLS are better than the responses from the reduced-order controller and PID tuned by ZN and TLC rules. Although there are many approaches for PID tuning, however, our proposed technique is an alternative method which directly considers the performance specifications and robustness in the design. Additionally, in the proposed technique, the structure of controller is not restricted to PID. The controller $K(p)$ can be replaced by any structure-specified controller and the proposed algorithm can still be applied functionally. Based on the concept of the convention HLS, only a single index, sta-

bility margin, ϵ , is used to indicate performance and robustness of the designed controller. In this paper, the stability margin obtained from the proposed controller is almost the same as that of HLS controller and is much better than that of the reduced-order controller. However, because of the complicated controller in the conventional design, the proposed approach offers a significant improvement in practical control viewpoint by simplifying the controller structure, reducing the controller order and still retaining the robust performance. Implementation on the pneumatic servo system verifies the effectiveness of the proposed controller.

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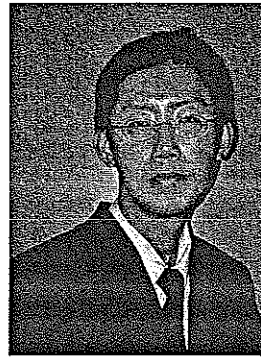
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