

Robustness of Hybrid Learning Acceleration Feedback Control Scheme in Flexible Manipulators

M. Z Md Zain, M. O. Tokhi, and M. S. Alam

Abstract—This paper describes a practical approach to design and develop a hybrid learning with acceleration feedback control (HLC) scheme for input tracking and end-point vibration suppression of flexible manipulator systems. Initially, a collocated proportional-derivative (PD) control scheme using hub-angle and hub-velocity feedback is developed for control of rigid-body motion of the system. This is then extended to incorporate a further hybrid control scheme of the collocated PD control and iterative learning control with acceleration feedback using genetic algorithms (GAs) to optimize the learning parameters. Experimental results of the response of the manipulator with the control schemes are presented in the time and frequency domains. The performance of the HLC is assessed in terms of input tracking, level of vibration reduction at resonance modes and robustness with various payloads.

Keywords—Flexible manipulator, iterative learning control, vibration suppression.

I. INTRODUCTION

FLEXIBLE robot manipulators exhibit many advantages over their rigid counterparts: they require less material, are lighter in weight, have higher manipulation speed, lower power consumption, require smaller actuators, are more manoeuvrable and transportable, are safer to operate due to reduced inertia, have less overall cost and higher payload to robot weight ratio. However, the control of flexible manipulators to maintain accurate positioning is challenging. Due to the flexible nature and distributed characteristics of the system, the dynamics are highly non-linear and complex. Problems arise due to precise positioning requirements, system flexibility leading to vibration, the difficulty in obtaining accurate model of the system and non-minimum phase characteristics of the system [1].

Many industrial applications of robot manipulators involve iterative repeated cycles of events. Thus, it is important to minimize errors in trajectory tracking of such manipulators, and this can be achieved with suitable learning

strategies. The basic idea behind iterative learning control (ILC) is that the controller should learn from previous cycles and perform better every cycle. Such ideas were first presented by Arimoto et al [2] in 1984 who proposed a learning control scheme called the improvement process, and since then several researchers have addressed robot control in combination with ILC, [3-5]. The convergence properties when using ILC control form another very important aspect, addressed already in [2], and further covered in many articles [6, 7]. In this paper ILC is studied to complement conventional feedforward and feedback control and the effectiveness of the resulting scheme is assessed in input tracking and vibration reduction in a flexible robot manipulator.

The paper presents investigations into the development of hybrid learning acceleration feedback control for input tracking and end-point vibration suppression of a flexible manipulator system. An experimental set up is used for evaluation of performance of the control strategies. To demonstrate the effectiveness of the proposed control schemes, initially a joint-based collocated PD control utilising hub-angle and hub-velocity feedback is developed for control of rigid body motion of the manipulator. This is then extended to incorporate an ILC scheme, with acceleration feedback using genetic algorithms (GAs) for optimization of the learning parameters for vibration suppression of the manipulator. Experimental results of the response of the manipulator with the controllers are presented in time and frequency domains. The performance of the HLC control is assessed in terms of input tracking, level of vibration reduction and robustness with various payloads in the experimental environment. Finally, a comparative assessment of the hybrid learning control scheme in input tracking and vibration suppression of the manipulator is presented.

II. THE FLEXIBLE MANIPULATOR SYSTEM

Figure 1 shows the laboratory-scale single-link experimental rig used in this work. This consists of three main components: a flexible arm and the driving motor, measuring devices and a digital processor. The flexible arm is constructed using a piece of thin aluminium alloy with length $L = 0.9$ m, width = 19.008 mm, thickness = 3.2004 mm, Young's modulus $E = 71 \times 10^9$ N/m², area moment of inertia $I = 5.1924$ m⁴, mass density per unit volume $\rho = 2710$ kg/m³ and hub inertia

M. Z. Md Zain is with The University of Sheffield, Automatic Control and Systems Engineering, Mappin Street S1 3JD Sheffield, UK (phone: +44-0114-222 5666; fax: +44-222-5661; e-mail: cop02mzm@sheffield.ac.uk).

M. O. Tokhi, was with The University Sheffield, Automatic Control and Systems Engineering, Mappin Street S1 3JD Sheffield, UK (e-mail: o.tokhi@sheffield.ac.uk).

M. S. Alam is with The University of Sheffield, Automatic Control and Systems Engineering, Mappin Street S1 3JD Sheffield, UK (e-mail: cop03msa@sheffield.ac.uk).

$I_h = 5.8598 \times 10^{-4} \text{ kgm}^2$. The manipulator can be considered as a pinned-free flexible arm, which can bend freely in the horizontal plane but is relatively stiff in vertical bending and torsion. The rig is equipped with a U9M4AT type printed circuit armature motor at the hub, driving the flexible manipulator. The motor is chosen as the drive actuator due to its low inertia and inductance and physical structure. Moreover, the printed armature gives a smooth torque output even at low speeds and the absence of magnetic material in the armature gives a linear torque to current relationship [8]. A linear drive amplifier LA5600 manufactured by Electro-Craft Corporation is used as a motor driver [9]. This is a bi-directional drive amplifier, as the motor needs to be driven in both directions to control the manipulator vibration.

The digital processor used is an IBM compatible PC based on an Intel(r) celeron™ processor. Data acquisition and control are accomplished through the utilization of PCL-812PG board. This board can provide a direct interface between the processor, actuator and sensors. The experimental set-up requires one analogue output to the motor driver amplifier and four analogue inputs from the hub-angle, hub-velocity, end-point acceleration and motor current sensor. The interface board is used with a conversion speed of 25 μs for A/D conversion and a settling time of 20 μs for D/A conversion, which are adequate for the system under consideration.



Fig. 1 The laboratory-scale single-link flexible manipulator

III. CONTROL SCHEMES

In this section, control schemes for rigid-body motion control and vibration suppression of the flexible manipulator are proposed. Initially, a collocated PD control is designed. This is then extended to incorporate an ILC scheme for control of vibration of the system.

A. Collocated PD Control

A common strategy in the control of manipulator systems involves the utilization of PD feedback of collocated sensor signals. Such a strategy is adopted at this stage of the investigation here. A block diagram of the PD controller is shown in Figure 2, where K_p and K_v are the proportional and derivative gains respectively. θ , $\dot{\theta}$ and α represent hub angle, hub velocity and end-point residual respectively, R_f is the

reference hub angle and A_c is the gain of the motor amplifier. Here the motor/amplifier set is considered as a linear gain A_c , as the set is found to function linearly in the frequency range of interest. In this study, the root locus approach is utilized to design the PD controller. Analyses of the root locus plot of the system show that dominant poles with maximum negative real parts could be achieved with $Z = K_p/K_v \approx 2$ and by setting K_p between 0 and 1.2 [10].

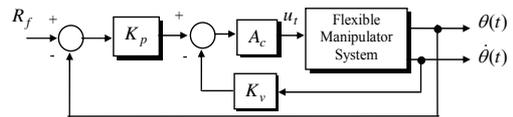


Fig. 2 The collocated PD control structure

B. Hybrid Learning Control Scheme

A hybrid collocated PD control structure for control of rigid-body motion of the flexible manipulator with ILC is proposed in this section. In this study, an ILC scheme is developed using PD-type learning algorithm. Iterative learning control has been an active research area for more than a decade. Learning control begun with the fundamental principle that repeated practice is a common mode of human learning. Given a goal (regulation, tracking, or optimization), learning control, or more specifically, iterative learning control refers to the mechanism by which necessary control can be synthesized by repeated trials. A typical learning algorithm is given as:

$$\Psi_{k+1} = \Psi_k + \Phi e_k + \Gamma \dot{e}_k \quad (1)$$

where Ψ_{k+1} is the next control signal

Ψ_k is the current control signal

e_k is the current positional error input, $e_k = (x_d - x_k)$, Φ, Γ are suitable positive definite constants (or learning parameters). It is obvious that the algorithm contains a constant and derivative coefficient of the error. In other words, the expression can be simply called proportional-derivative or PD type learning algorithm. A slightly modified learning algorithm to suit the application is employed here. Instead of using the absolute position tracking error e_k , a sum-squared tracking error is used. A PD type algorithm may be represented as shown in Figure 3. This is used with PD collocated control, to realise the hybrid collocated PD with learning algorithm. This is shown in Figure 4, and referred to as HLC.

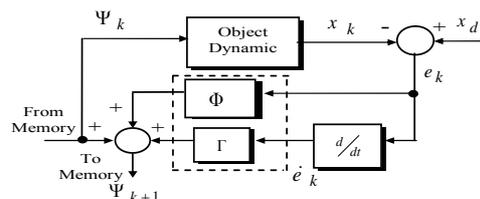


Fig.3 PD type learning algorithm

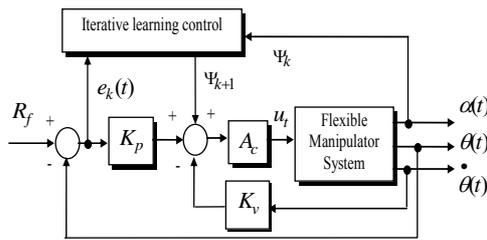


Fig. 4 The hybrid learning acceleration feedback control structure

C. GA Based Hybrid Learning Control

Figure 4 shows the PD-type learning control scheme. The performance of a PD-type learning control depends upon the proportional gain Φ and derivative gain Γ . This includes the stability, settling time, maximum overshoot and many other system performance indicators. The proposed strategy utilizes genetic algorithm (GA) as an optimization and search tool to determine the optimum values of the gains. The performance index or the cost function chosen is the error in the system output to reach and stay within a range specified by absolute percentage of the final value. Hence, the role of GA is to find optimum values of gains Φ and Γ . In this case, integral of absolute error (IAE) is used as the criterion for minimising the error:

$$IAE = \int_0^T \left| \frac{\sum Error^2}{N} \right| dt \quad (2)$$

where, Error = $r(t) - y(t)$, N = number of samples, $r(t)$ = reference input and $y(t)$ = measured output. The above error criterion is used with GA based tuning. The GA initializes a random set of population of the two variables. The algorithm evaluates all members of the population based on the specified performance index. The algorithm then applies GA operations such as reproduction, crossover and mutation to generate a new set of population based on the performance of members of the population [11]. The best member or gene of the population is chosen and saved for next generation. It again applies this operators and selects the best gene among the new population. The best gene of the new population is compared to best gene of previous population. If a predefined termination criterion is not met, again a new population is obtained as above. The termination criterion may be formulated as the magnitude of difference between index value of previous generation and present generation becoming less than a pre-specified value. The process continues till the termination criterion is fulfilled.

IV. RESULTS AND DISCUSSION

In this section, the proposed control schemes are implemented and tested within an experimental environment of the flexible manipulator and the corresponding results are presented. The manipulator is required to follow a trajectory at $\pm 75^\circ$ as shown in Figure 5. System responses, namely hub-angle and end-point acceleration are observed. To assess the

vibration reduction in the system in the frequency domain, power spectral density (SD) of response at the end-point is obtained. The first three modes of vibration of the system are considered as dominantly characterising the behaviour of the manipulator. Figure 6 shows the experimental response of the manipulator. The vibration frequencies of the system were obtained as 13, 35 and 65 Hz without payload and 11, 33 and 62.3 Hz with 15 g payload. These results were considered as the system response in open loop and subsequently used to evaluate the control techniques.

The collocated PD control scheme was designed based on root locus analysis, from which K_p , K_v and A_c were deduced as 2.4, 1.2 and 1 respectively. The corresponding system response without and with payload is shown in Figure 6. The closed-loop parameters with the PD control were used to design and evaluate the performance of iterative learning acceleration feedback control schemes in terms of input tracking capability and level of vibration reduction. The results in Figure 6 for the collocated PD control will be used for comparative assessment of the hybrid control schemes proposed in section III. The (HLC) scheme was designed on the basis of the dynamic behaviour of the closed-loop system. The parameters of the learning algorithm, Φ and Γ were tuned using GA. The parameters used for experimental systems were as: $\Phi = 0.0015$, $\Gamma = 0.0011$. The fixed PD controller and learning parameter in this case have optimum performance only for a certain loading condition of the flexible manipulator.

The GA was designed with 80 individuals in each generation. The maximum number of generations was set to 100 for without payload. The algorithm achieved a minimum IAE level in the 70th generation. Figure 7 shows the algorithm convergence as a function of generations. The corresponding responses of the manipulator without and with payload with HLC are shown in Figures 6. It is noted that the proposed hybrid controller with learning algorithm is capable of reducing the system vibration while resulting in better input tracking performance. The vibration of the system settled within less than 3 s, which is much less than that achieved with PD control. Figure 8 shows the level of vibration reduction with the end-point acceleration responses at the resonance modes of the closed-loop systems as compared to open-loop response for the manipulator.

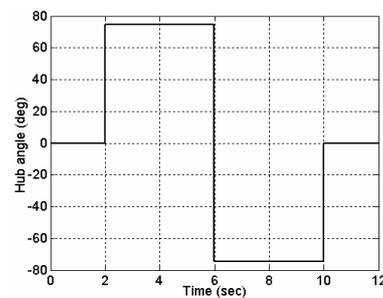


Fig. 5 The reference hub angle

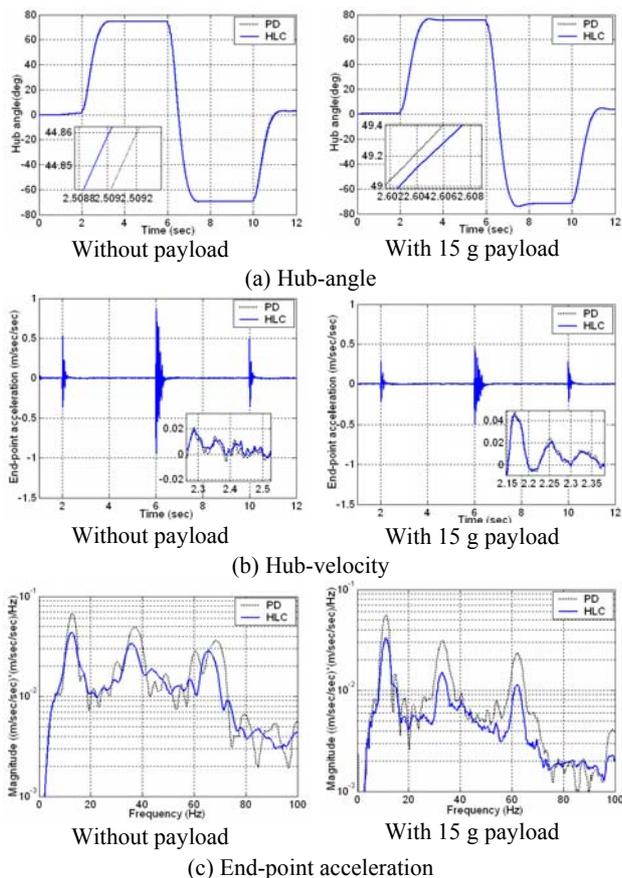


Fig. 6 Response of the experimental manipulator system without and with 15 g payload

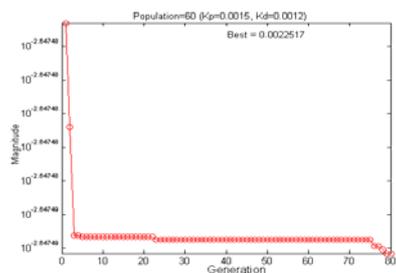


Fig. 7 Objective value vs number of generation

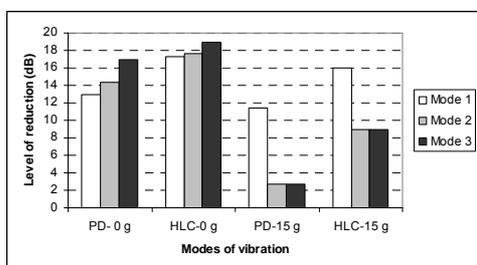


Fig. 8 Vibration reduction with the control techniques in various payloads

V. CONCLUSION

The development of hybrid learning acceleration feedback control schemes for input tracking and vibration suppression of a flexible manipulator has been presented. The control schemes have been developed on the basis of collocated PD with ILC based on GA optimization and input shaping. The control schemes have been implemented and tested within an experimental environment of a single-link flexible manipulator without payload. The performances of the control schemes have been evaluated in terms of input tracking capability and vibration suppression at the resonance modes of the manipulator. Acceptable input tracking control and vibration suppression have been achieved with both control strategies. A comparative assessment of the control techniques has shown that HLC scheme results in better performance than the PD control in respect of hub-angle response and vibration suppression of the manipulator. Moreover, the system response rise time is longer in each case as compared to PD with a payload. Future work in a related field will include adaptive control to achieve better system performance for various loading conditions.

REFERENCES

- [1] Book WJ, Majette M., *Controller design for flexible distributed parameter mechanical arm via combined state-space and frequency domain techniques*. Transactions of ASME: Journal of Dynamic Systems, Measurement and Control 1983; 105(4): 245-254.
- [2] Arimoto S., Kawamura S., and Miyazaki F., *Bettering operation of robots by learning*, Journal of Robotic Systems, 1984; 1(2):123-140.
- [3] Craig J. J., *Adaptive Control of Mechanical Manipulators*, Addison-Wesley Publishing Company, 1988.
- [4] Horowitz R., *Learning control of robot manipulators*, Journal of Dynamic Systems, Measurement, and Control, June 1993; 115: 402-411.
- [5] Panzieri S. and Ulivi G., *Disturbance rejection of iterative learning control applied to trajectory tracking for a flexible manipulator*. In Proceedings of 3rd European Control Conference, ECC, September 1995, pages 2374-2379.
- [6] Amann N., Owens D. H., and Rogers E., *Iterative learning control for discrete time systems with exponential rate of convergence*. Technical Report 95/14, Centre for Systems and Control Engineering, University of Exeter, 1995.
- [7] Gunnarsson S. and Norrlöf M. A short introduction to iterative learning control. Technical Report LiTH-ISY-R-1926, Department of Electrical Engineering, 1997.
- [8] PMI Motion Technologies, *General Application of Printed Motors*, (PMI Motion Technologies, New York), 1988.
- [9] Electro-craft Corporation. *DC Motor Speed Control Servo Systems*, (Electro-craft Corporation/Robbins and Mayers, Minnesota), 1985.
- [10] Azad K. M., *Analysis and design of control mechanisms for flexible manipulator systems*. PhD thesis, Department of Automatic Control and Systems Engineering, The University of Sheffield, 1994.
- [11] D. Garg, and M. Kumar, "Optimal Path Planning and Energy Minimization via Genetic Algorithm Applied to Cooperating Manipulators", Proceeding of ASME, Special Publication of DSCD/ASME, Paper No. IMECE2001/DSC-24509, 2001.