Pole Selection of Feedforward Compensators Considering Bounded Control Input of Industrial Mechatronic Systems

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***Abstract*—A new pole selection method for feedforward compensators of mechatronic servo systems is presented in this paper. It is necessary to have the system poles located at desirable positions on the *s-plane* in order to realize better servoing performance. However, selection of new poles is not a straightforward problem and in most industrial mechatronic systems, it has been a mere cut-and-dry procedure. In this research, feedforward compensator poles are related to the control input, and a criterion was developed to determine the desirable poles that improve the control input within its limits. This method was developed for the second-order model and it was simulated and experiments were performed with the Performer MK3s articulated industrial robot manipulator. Some attractive results have been obtained with the new method.**

***Index Terms*—Control input, feedforward compensator, industrial mechatronic servo system, pole selection.**

I. Introduction

THE performance of industrial mechatronic servo systems is determined by the dominant poles, which are closer to the origin of the s-plane. The presence of at least one such pole makes the mechatronic system "slow responding." In such systems, control input is weak and long lasting with slowly decaying characteristics. These characteristics are critically troublesome in servoing operations of mechatronic systems where fast response is required. To make the system "fast responding," system poles should be located on the negative half of the s-plane, further away from the imaginary axis. Such a pole would make a strong and fast decaying control input so that the system responds quickly. However, it should also be guaranteed that the pole selection does not raise the control input unnecessarily high toward saturation. In this view, the desirable poles can be selected at the limit of control input saturation.

As described by Khane [1], poles can be assigned by means of: 1) state/output feedback or 2) feedforward compensator based on pole–zero cancellation. Pole placement with state feedback [2]–[4] was developed on the internal model (state space) of the system. It takes all state variables, multiplied by feedback gains and used together with the reference input to decide the control input. On the s-plane, feedback gains relocate the closed-loop poles. In this view, feedback gains could be determined in such a way that system poles are located at desirable locations. However, in general, there is no way to know *a priori* the desirable pole location for a given application. Thus, a performance index is usually defined, which in most formulations is an integral of a quadratic function of weighted state variables and weighted control inputs [linear quadratic regulator (LQR). Then, the optimization problem is to iteratively optimize the performance index over the entirety of operation and converge to optimum feedback gains [5]. However, a state feedback controller needs as many sensors/transducers as there are state variables and it makes them sophisticated and expensive devices. Further, all state variables are seldom available for feedback. Therefore, the output feedback method [4], which needs only the measured outputs, was developed. However, output feedback does not guarantee a better overall performance than full state feedback [4]. Thus, Yuan *et al.* [6] extended the output feedback method and came up with an algorithm that assigns poles within a specified region on the s-plane and guaranteed desired closed-loop performance.

A feedforward compensator with pole–zero cancellation is the other means of pole placement. Pole–zero cancellation needs an accurate transfer function of the system, based on which the feedforward compensator introduces a new set of zeros and poles where the zeros are set to be coincident with the troublesome poles of the uncompensated system. Thereby, the troublesome poles can be cancelled and new poles can be arbitrarily and optimally assigned based on any optimization criterion [2]. Somehow, pole–zero cancellation may lead to serious stability problems as indicated by Clarke [7] and Kahne [1], if it is implemented blindly. However, the present mechatronic industry widely adapts feedforward compensators based on pole–zero cancellation, and conveniently employs them without leading to stability problem. Actually it has been successfully employed by Nakamura *et al.* [8] for positioning control of a SCARA robot, by Munasinghe *et al.* [9], [10] for positioning and path-following applications of an articulated manipulator, and also by Jenkins *et al.* [11] for force control in grinding processes.

Bounded control input is inevitable in all practical control systems. Negligence of it in controller design would certainly deteriorate system performance. Some pioneering consideration on this problem have been accomplished by Ohkawa *et al.* [12] and Payne [13]. Thorough consideration of bounded control input in adaptive pole placement can be found in [14], [15],

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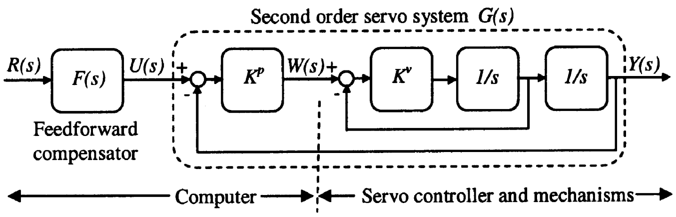


Fig. 1. Second-order servo system with feedforward compensator.

and [16] with particular concern for stability and system performance. Pole placement based on feedback techniques in view of bounded control input can be found in [17], [18], and [19]. However, all these previous works have been mostly limited to theoretical derivations with a few exceptions that have provided examples and simulations. None of them have been tested with appropriate experiments and the tremendous work so far has also focused on slowly varying reference sequences such as plant regulation, which accepts some amount of initial saturation. However, in mechatronic servo applications, reference trajectories are usually fast varying sequences and the ability to regulate them is only an essential condition but not sufficient. Actually, in servo applications, transient behavior should be thoroughly considered in the controller/compensator design which should confirm that unsaturated control input be maintained within the entire operation.

In this research, we have identified the relationship between feedforward compensator poles and control input, and developed a theoretical criterion to select the desirable poles bound to the maximum control input. The new compensator was simulated and successfully experimented for servoing applications with a Performer MK3s articulated manipulator.

II. Overview of Industrial Mechatronic Servo Systems

A. *Mechatronic Servo System and Feedforward Compensator*

A typical second-order mechatronic servo system with a feedforward compensator is shown in Fig. 1. The trajectories $R(s)$, $U(s)$, $W(s)$, and $Y(s)$ are the realizable trajectory (known as "taught data" in industry), modified realizable trajectory (known as "modified taught data" in industry), control input, and following trajectory, respectively. The objective trajectory of the servoing task is usually given *a priori* as a set of points in Cartesian three-dimensional space. It is a commonplace fact that the objective trajectory possesses unrealizable features such as sharp corners that the end-effector cannot follow unless it stops momentarily. There also exist kinematic specifications for various applications which are either to be fulfilled or not to be violated within the entire servoing [10]. Therefore, a trajectory planner is usually incorporated to consider unrealizable features and specifications, and to plan a realizable trajectory $R(s)$. The realizable trajectory is modified by the feedforward compensator in order to obtain a modified realizable trajectory $U(s)$, which could realize fast system response so that $Y(s)$ follows $R(s)$ as closely as possible.

Fig. 1 illustrates the second-order servo system $G(s)$ with the feedforward compensator $F(s)$ in which

$$G(s) = \frac{K^p K^v}{(s^2 + K^v s + K^p K^v)}. \quad (1)$$

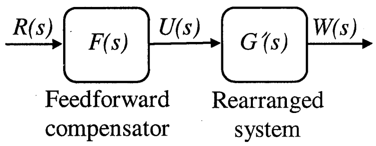


Fig. 2. Rearranged system with control input $W(s)$ at the output.

The two servo parameters K^p and K^v are the feedback gains of position and velocity loops. The poles of the uncompensated second-order system $G(s)$ are given by $(-K^v \pm \sqrt{(K^v)^2 - 4K^p K^v})/2$, and the fastest response could be obtained by critically damping the system by setting $K^p = (1/4)K^v$ so that the two system poles become real and coincident at $-K^v/2$. However, K^v is a manufacturer specification, which remains within the servo controller as shown in Fig. 1, and the user is not supposed to manipulate it. Therefore, in order to relocate poles, a feedforward compensator $F(s)$ is incorporated as illustrated in Fig. 1. The role of this compensator is to cancel existing poles, and assign new poles at desirable locations. In practical terms, $F(s)$ modifies the realizable trajectory $R(s)$ in order to compensate the delay in dynamics.

A typical feedforward compensator as proposed by Goto *et al.* [21] can be written in the form of

$$F(s) = \frac{\mu_1 \mu_2 (s^2 + K^v s + K^p K^v)}{K^p K^v (s - \mu_1)(s - \mu_2)} \quad (2)$$

where the numerator cancels the existing poles of the uncompensated system $G(s)$ while the denominator assigns the new poles μ_1, μ_2. The gain of the compensator $\mu_1 \mu_2 / (K^p K^v)$ confirms zero steady-state error for a unit step input. Feedforward compensators play a key role in widely practiced "semi-closed" type mechatronic applications where only servo motor kinematics are used to control the required end-effector performance. As can be imagined, a highly nonlinear transformation exists between motor kinematics and end-effector kinematics. Thus, in semi-closed control, fast and accurate servo motor control is essential to guarantee desirable end-effector performance. The compensated system gives a sufficient accuracy, robustness, and convenient implementation in mechatronic systems. Thus, it is widely used in current industrial mechatronic systems for the purpose of controller construction [20]. Almost all industrial mechatronic systems are designed to assume real stable poles. Thus, cancellation of unstable poles and instability problems due to inexact cancellation of unstable poles are not crucial issues in industry.

B. *Problem Statement*

The problem considered in this paper is to select the desirable pole(s) of the feedforward compensator $F(s)$, considering the limits of control input $W(s)$. It is also assumed that the required parameters of the realizable trajectory $R(s)$ and uncompensated system $G(s)$ are known. The system in Fig. 1 can be rearranged so that the control input $W(s)$ appears at the output as shown in Fig. 2. The rearranged system can be written as

$$G'(s) = \frac{s(s + K^v)}{(s^2 + K^v s + K^p K^v)}. \quad (3)$$

In mechatronic servo applications, fast response is required while avoiding overshoots and oscillations. Therefore, the condition of critical damping is required. The system can be damped critically by having coincident real poles in the feedforward compensator ($\mu_1 = \mu_2 = \mu$). Then, from Fig. 2, control input $W(s)$ can be written as

$$W(s) = R(s)F(s)G'(s) \tag{4}$$

$$= \frac{R(s)\mu^2 s(s+K^v)}{\{K^v(s-\mu)^2\}}. \tag{5}$$

However, in all industrial systems, control input $w(t)$ is bounded by the hardware, and constrained as given by

$$|w(t)| \leq w_m \tag{6}$$

where w_m is the allowed maximum control input. Then, the objective can be narrowed down to develop an appropriate criterion to select the desirable compensator pole μ_m without violating constraint (6).

III. Feedforward Compensator Design

A. *Differential Input Trajectory and Control Input*

In industrial mechatronic servo systems, a realizable trajectory (reference input) is generally a time-based zeroth-order hold (ZOH) sequence as shown in Fig. 3(a). Realizable trajectory $r(t)$ can be decomposed into a series of time-shifted differential step inputs as shown in Fig. 3(b). Then, $r(t)$ can be written as a summation of differential inputs as given by

$$r(t) = \sum_{i=0}^{N-1} \Delta r_i u(t - iT) \tag{7}$$

where

$$\Delta r_i = r_i - r_{i-1}$$

$$u(t-iT) = \begin{cases} 0, & t < iT \\ 1, & t \geq iT. \end{cases}$$

Symbol T stands for the sampling interval and N is the total number of differential inputs in the series. On the other hand $NT[s]$ is the total time of the servoing operation. The index i is the index of individual differential input components. Using the summation form, realizable trajectory $r(t)$ in (7) can be easily transformed into the Laplace domain as

$$R(s) = \sum_{i=0}^{N-1} R_i(s) \tag{8}$$

where

$$R_i(s) = \frac{\Delta r_i e^{-iTs}}{s}. \tag{9}$$

Using (2) and (3) in (4) and (9) in (5), control input for a single differential input $\Delta r_i u(t - iT)$ can be derived in both Laplace and time domains as

$$W_i(s) = \Delta r_i \mu^2 e^{-iTs} \frac{(s+K^v)}{K^v(s-\mu)^2} \tag{10}$$

$$w_i(t) = \Delta r_i \mu^2 e^{\mu(t-iT)}\{1 + (t-iT)(K^v+\mu)\} \times \frac{u(t-iT)}{K^v}. \tag{11}$$

Individual control inputs derived in (11) are illustrated in Fig. 3(c). The net control input $w(t)$ at any instant can be derived using superposition of all individual control inputs $w_i(t)$ as

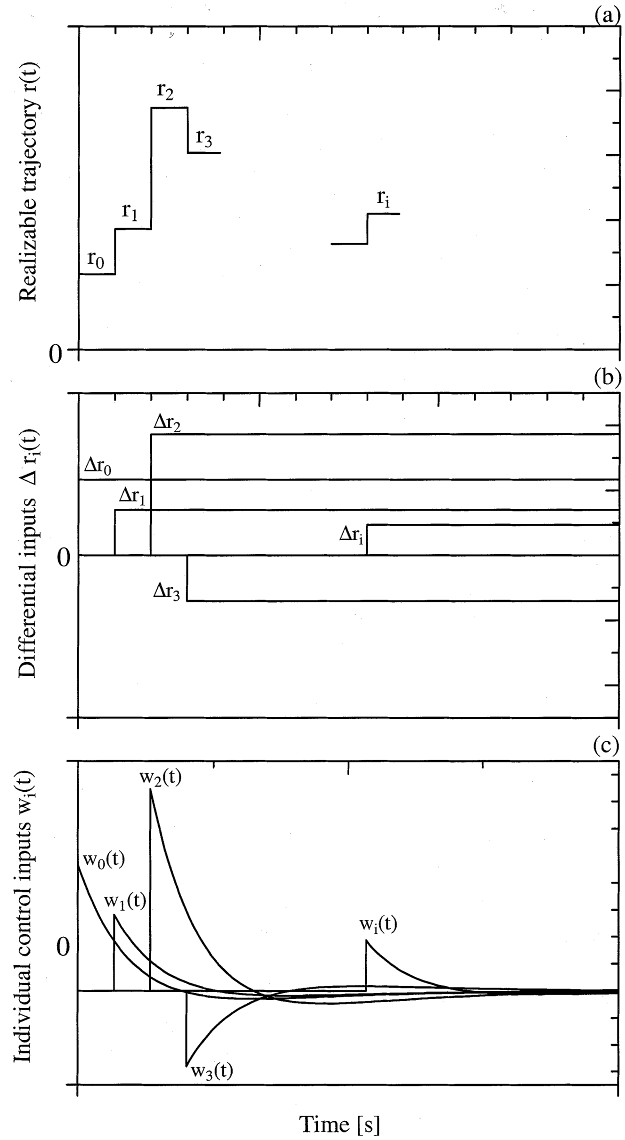


Fig. 3. Some typical trajectories. (a) Realizable trajectory $r(t)$. (b) Differential inputs $\Delta r_i(t)$. (c) Individual control inputs $w_i(t)$ for each $\Delta r_i(t)$.

$$w(t) = \sum_{i=0}^{N-1} w_i(t). \tag{12}$$

In discrete systems, control input $w(nT)$ at any discrete time $t = nT$ is required. The index $n; n \in [0, N-1]$ is the index for discrete time. It follows from (12) that superposition could be applied in order to determine the discrete control input as

$$w(nT) = \sum_{i=0}^{N-1} w_i(nT). \tag{13}$$

The discrete control input $w_i(nT)$ can be determined from (11) as

$$w_i(nT) = \Delta r_i \mu^2 e^{\mu(n-i)T}\{1 + (n-i)T(K^v+\mu)\} \times \frac{u(t-iT)}{K^v}. \tag{14}$$

However, as described in (11) and also illustrated in Fig. 3(c), individual control inputs $w_i(t)$ decay with time. Thus, it is possible to resolve the summation in (13) as

$$w(nT) = \sum_{i=0}^{n-\eta-1} w_i(nT) + \sum_{i=n-\eta}^{n} w_i(nT) + \sum_{i=n+1}^{N-1} w_i(nT) \tag{15}$$

where the first summation possesses individual control inputs that have already been decayed to zero by $t = nT$. The third summation possesses individual control inputs that are yet to appear. Only the recently preceded control inputs are included in the second summation, and they are in possession of nonnegligible magnitudes at $t = nT$. Therefore, eliminating the first and third summations, an accurate approximation of discrete control input can be obtained as

$$w(nT) \approx \sum_{i=n-\eta}^{n} w_i(nT) \tag{16}$$

where ηT is the time any individual control input would take to sufficiently decay out. Then, the discrete control input can be written by substituting (14) in (16) as

$$w(nT) \approx \sum_{i=n-\eta}^{n} \mu^2 \Delta r_i e^{\mu(n-i)T} \times \{1 + (n-i)T(K^v + \mu)\} \frac{u(t-iT)}{K^v}. \tag{17}$$

It is clear by now that the number of individual components to be considered in the discrete control input has been significantly reduced without loss of accuracy. To evaluate the summation in (17) we make the assumption that $\Delta r_i = \Delta r \quad \forall\, i = [n-\eta, n]$. We also use the time-invariant property to shift the summation limits from $\{n-\eta, n\}$ to $\{0, \eta\}$, for convenience. Then, (17) can be rewritten as

$$w(nT) \approx \mu^2 \Delta r \sum_{i=0}^{\eta} e^{\mu(\eta-i)T} \times \{1 + (\eta-i)T(K^v + \mu)\} \frac{u(t-iT)}{K^v}. \tag{18}$$

Then, the summation can be evaluated to arrive at (19), shown at the bottom of the page. From (19), it is clear that the control input $w(nT)$ is affected by compensator pole μ, sampling interval T, differential input Δr, velocity feedback gain K^v, and the number of significant control inputs η. The following guidelines are worth considering at this point.

1) Sampling interval T is determined within the trajectory planning.
2) Maximum differential input Δr_m is directly obtained from the realizable trajectory $R(s)$.
3) Velocity feedback gain K^v is a manufacturer setting, which is known but not supposed to be manipulated.
4) A criterion is required to determine an appropriate value for η.

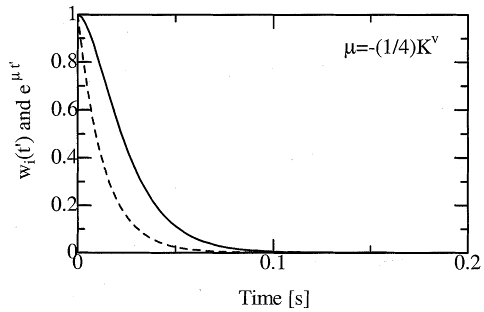


Fig. 4. Decay characteristics of control input $w_i(t')$ and its exponential term $e^{\mu t'}$ for the uncompensated, critically damped system.

B. Determination of η

A practical value for η can be determined by analyzing the decay characteristics of (11). By time shifting with new time variable $t' = t - iT$, and setting initial magnitude to unity, the percentage magnitude of control input $\%w_i(t')$ can be written as

$$\%w_i(t') = e^{\mu t'}\{1 + t'(K^v + \mu)\}u(t'). \tag{20}$$

With respect to the decaying characteristics of $\%w_i(t')$, the exponential term $e^{\mu t'}$ dictates over its proportional term $t'(K^v + \mu)$. It is deduced that $\lim_{t'\to\infty} \%w_i(t') = \lim_{t'\to\infty} e^{\mu t'} = 0$, and Fig. 4 illustrates how the control input and its exponential term decay out. At very small magnitudes $\%w_i(t') \approx e^{\mu t'}$. Therefore, a sufficiently small magnitude p and corresponding decay time t'_p could be related by $p \approx e^{\mu t'_p}$. Then, using the pole setting of the uncompensated system, η can be determined from $p = e^{-(1/2)K^v \eta T}$, which can be reduced to integer

$$\eta = \left\lceil \frac{-2\ln(p)}{(K^v T)} \right\rceil. \tag{21}$$

This way, the value calculated for η is large enough for pole settings which are greater in magnitude than the poles of the uncompensated, critically damped system.

Using η determined from (21), and setting differential input as $\Delta r = \Delta r_m$, the expected peak control input can be determined from (19) as a function of compensator pole μ. This is a monotonically increasing function, and the desirable pole can be selected graphically at the point where peak control input reaches the allowed limit of control input w_m. The criterion for pole selection can then be formulated as

$$\mu_m \approx \max\{\mu | \Delta r = \Delta r_m, |w(nT)| \le w_m\}. \tag{22}$$

$$w(nT) \approx \mu^2 \Delta r \frac{\left[(1 - e^{\mu(\eta+1)T})(1 - e^{\mu T}) + T(K^v + \mu)e^{\mu T}\{1 - (\eta+1)e^{\mu\eta T} + \eta e^{\mu(\eta+1)T}\}\right]}{K^v(1 - e^{\mu T})^2} \tag{19}$$

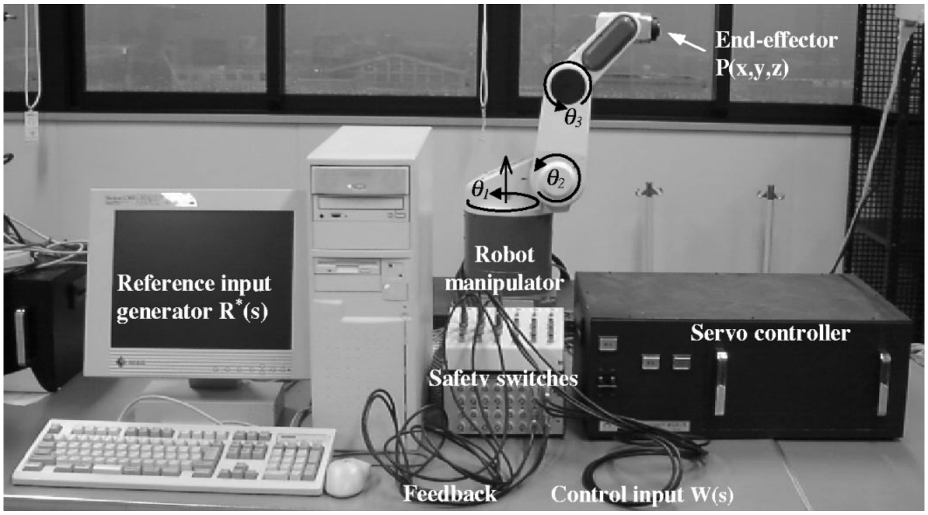


Fig. 5. Performer MK3s industrial robot manipulator.

In [15] and [22], similar techniques have been considered, where online readjustment of the reference increments was used to avoid control input saturation. However, in fast servoing applications, online trajectory planning is not generally recommended.

IV. Implementation of the Proposed Method

A. End-Effector Trajectory

Experiments with he proposed method were conducted with the Performer MK3s articulated industrial manipulator. This manipulator is controlled by individual proportional–integral–derivative (PID) servo drives attached to each joint $(\theta_1, \theta_2, \theta_3)$. With a feedforward compensator, it could perform better with a sophisticated computed torque control [23]. The experimental setup is shown in Fig. 5 where the important system components are labeled. The reference input generator is a computer which carries out trajectory planning and constructs the realizable trajectory $R(s)$. It also implements feedforward compensator $F(s)$, and engage in online servoing where it computes the error between time-based samples of the modified realizable trajectory $U(s)$ and the joint position feedback. Based on this position error, it computes control inputs for each individual joint, and sends them to the servo controller. The servo controller actuates the joint servo motors $(\theta_1, \theta_2, \theta_3)$ of the robot manipulator ("semi-closed control") so that the end-effector $P(x, y, z)$ follows the realizable trajectory in Cartesian space. Safety switches are provided to halt the systems in an emergency.

The objective trajectory used in this research was the sequence of Cartesian points specified by start (0.35, 0.00, 0.10) [m], corner 1 (0.41, 0.10, 0.15) m, corner 2 (0.28, −0.10, 0.30) m, and end (0.35, 0.00, 0.35) m. Using the trajectory planning algorithm in [24], the two sharp corners were rounded up with the radii of arc 7.5 and 7.4 mm. The sampling interval used was $T =$ 2 ms. The realizable trajectory was so constructed that the end-effector velocity and joint accelerations are maintained within *a priori* given limits. The constructed realizable trajectory $R(s)$ is shown in Fig. 6, where it undergoes the maximum differential input at $t = 1.972$ s as indicated. Fig. 7 shows some important details of the realizable trajectory $R(s)$: 1) end-effector velocity; 2) accelerations of the second joint; and 3) differential input profile of the second joint. According to the realizable trajectory, the second joint undergoes the maximum differential input as indicated in Fig. 7(c). Therefore, if the second joint can be actuated without having control input saturation, the other two joints would certainly perform safely. As shown in Fig. 7(a), indicated by $\rightarrow A$, end-effector accelerates within the interval [1.576 s, 1.972 s]. This is the result of having it actuated with the maximum deceleration of 1.5 rad/s^2 as indicated by $\rightarrow B$ in Fig. 7(b). As a result, the second joint undergoes an increasing magnitude in its differential input until it reaches a maximum $|\Delta r_m| = 0.072$ rad at $t = 1.972$ s as indicated in Figs. 6 and 7(c) where the end-effector reaches the assigned (limiting) velocity 2.5 m/s (set *a priori* within the trajectory planning).

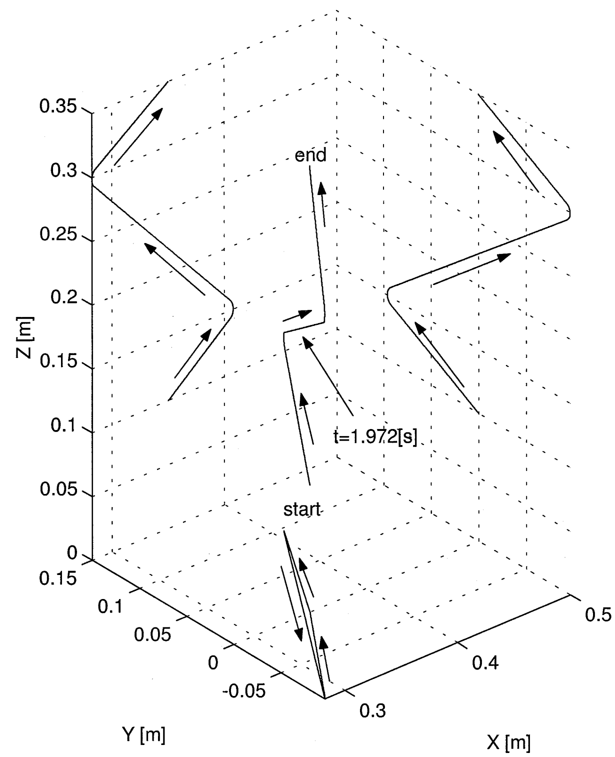


Fig. 6. Realizable trajectory $R(s)$ in three-dimensional Cartesian space. Maximum differential input Δr_m occurs at $t = 1.972$ s.

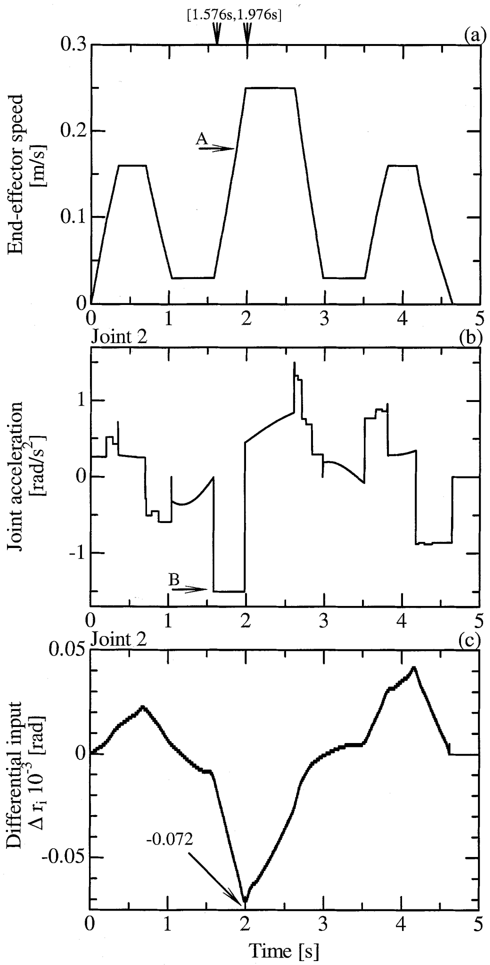


Fig. 7. Reference trajectory $r(t)$. (a) End-effector velocity. (b) Joint-2 acceleration. (c) Joint-2 differential input trajectory.

Trajectory planning remains outside the scope of this research. Once the trajectory planning has been completed, maximum differential input Δr_m is known, and the problem remaining after trajectory planning is to select the desirable compensator pole(s) considering the known Δr_m and control input limit w_m.

B. Pole Selection

Trajectory planning specified $T = 2$ ms, and the Performer MK3s has its velocity feedback gain setting $K^v = 150$. Then, setting $p = 0.0001$ (i.e., 0.01% decay), $\eta = 62$ was determined from (21).

With control input constraint set to $w_m = 0.7$ rad/s, the peak control input in (19) was plotted against $\mu \in [-(1/2)K^v, -(3/2)K^v]$. The result is shown in Fig. 8. The desirable pole was selected as $\mu_m = -165$ at the point where the peak control input intersects the allowed maximum control input. Besides the graphical search method, Newton–Raphson method can be applicable with $f(\mu) = w(nT) - m_w = 0$ and iterative search $\mu_{k+1} = \mu_k - f(\mu_k)/f'(\mu_k)$, where k is the iteration index. The initial approximation can be made to $\mu_0 = -(1/2)K^v$, which is the pole seting of the uncompensated system. Gradient $f'(\mu_k) \approx \{f(\mu_k + \Delta\mu) - f(\mu_k)\}/\Delta\mu$ can also be used with sufficiently small $\Delta\mu$.

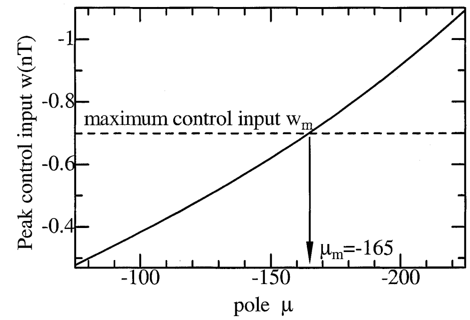


Fig. 8. Control input variation against pole.

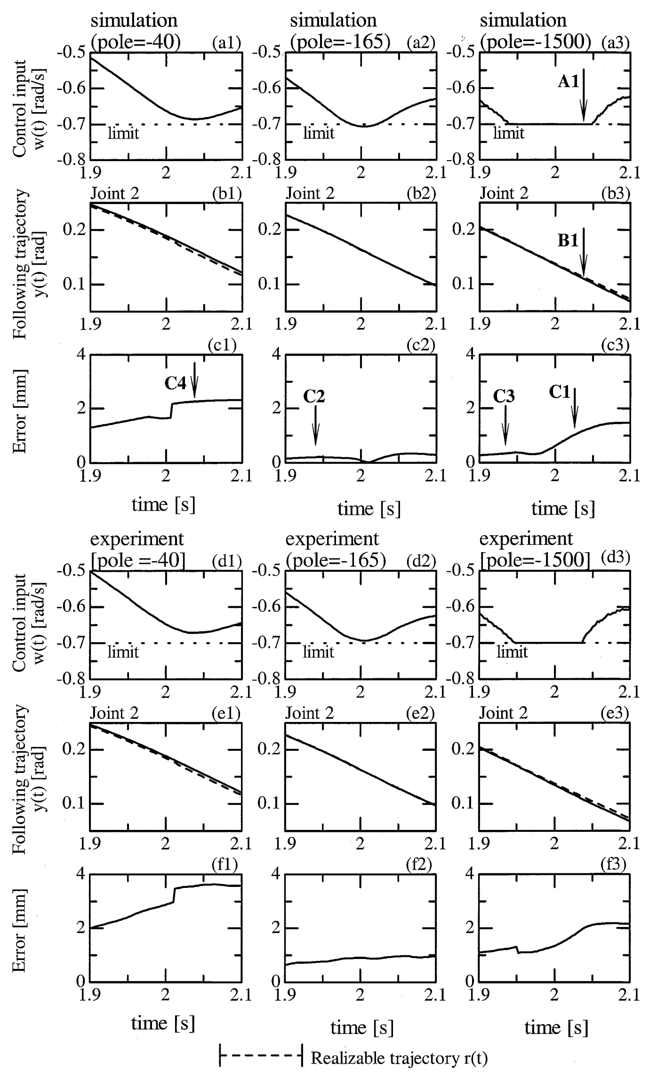


Fig. 9. Simulation and experimental results of control input $w(t)$, realizable $r(t)$ and following $y(t)$ trajectories of joint 2, and trajectory error in Cartesian coordinates.

V. Results and Discussion

A. Results

Fig. 9 illustrates simulation and experimental results of joint–2 control input, following trajectory and realizable trajectories of joint 2, and trajectory error in Cartesian space. For clear comparison and evaluation reasons, simulation and experiment were carried out for three different pole settings as $\mu = -40$ (too small), -165 (desirable) and -1500 (excessive).

TABLE I
CONTOURING ERROR IN RMS FORM

μ=-40	μ=-165	μ=-1500
3.03 [mm]	0.64 [mm]	1.63 [mm]

As indicated by $\downarrow\ A1$ in Fig. 9(a3), excessive pole setting causes control input saturation. It causes the following trajectory $y(t)$ to deviate off the realizable trajectory $r(t)$ as indicated by $\downarrow B1$ in Fig. 9(b3). Consequently, it gives rise to trajectory error as indicated by $\downarrow C1$ in Fig. 9(c3). It is also interesting to examine and compare the performance with optimum and excessive pole setting. As indicated by $\downarrow C2$ in Fig. 9(c2) and $\downarrow C3$ in Fig. 9(c3), the two error profiles are more or less comparable before saturation takes place, and error starts increasing after saturation. In case of the small pole setting, the system shows a delay as indicated by $\downarrow B2$ in Fig. 9(b1) which gives an excessive Cartesian error in the end-effector performance as indicated by $\downarrow\ C4$ in Fig. 9(c1). The above interpretation of simulation results can be extended to experimental results as simulation and experimental results comply with each other. However, experimental results show a greater magnitude in error profiles than those of simulation results. This effect can be attributed to the unmodeled dynamics of the system. Contouring error within the interval [1.576 s, 1.976 s] in root mean square form is given in Table I.

B. Discussion

The proposed pole selection procedure can be adopted with any offline trajectory planning algorithm. Trajectory planning provides realizable trajectory $R(s)$ from which the maximum differential input Δr_m is directly obtained. Using maximum differential input, the peak control input can be determined for a given pole setting, and the desirable poles are selected graphically, when the peak control input intersects with the limit of control input w_m. This way, the compensated system is critically damped at a better pole location. This procedure can be applicable to a vast number of mechatronic applications as most of them demonstrate characteristics similar to those explained above.

Feedforward compensators are generally not recommended for cancellation of unstable poles [2] in that inexact cancellation (which is almost inevitable) would make the system unstable. However, almost all industrial mechatronic servo systems are designed to have stable poles, and, the problem discussed here is their closeness to the origin of the s-plane, which makes the system slowly responding, thereby failing to carry out fast servoing operations. Cancellation of troublesome stable poles is used to eliminate their appearance at the output. However, even with the exact pole–zero cancellation, such hidden modes would appear at the output due to the following reasons: 1) nonzero initial conditions and 2) nonlinear behavior of some signals within the system [7]. The following guidelines describe how industry adopts pole–zero cancellation with concern for the above demerits.

1) The process is initialized to zero initial state so that hidden modes due to cancelled poles cannot appear at the output with the help of the initial states.
2) It is guaranteed by the proposed criterion that the control input is confined to its linear behavior within servoing. Therefore, without nonlinearity in signals, hidden modes cannot make their appearance at the output.

The uncompensated system $G(s)$ shows zero steady-state error for step inputs. The gain setting μ^2/K^vK^p of the compensator guarantees the same zero steady-state error. Having coincident poles makes the compensated system critically damped, thus realizing the fastest performance without overshoots and oscillations. The proposed feedforward compensator does not affect the system order either. In this view, with specific care taken against all drawbacks of pole–zero cancellation, a feedforward compensator could be designed and optimized bound to the constraint of control input.

VI. CONCLUSION

A new method for the pole selection of a feedforward compensator has been theoretically developed based on the control input limit of mechatronic servo systems. The method has been simulated and then experimentally proven for proper functionality. In most industrial mechatronic applications, pole placement has been a cut-and-dry procedure based on practitioner intuition. With the new method, feedforward compensator poles could be selected avoiding trial-and-error procedures. The new method is convenient to implement in the mechatronic industry, as it does not ask for hardware changes. The only rearrangement required is the offline trajectory processing for the feedforward compensator, which will be a simple program code that resides in the reference input generator. With ease of implementation, being free of cost and risk, and also having guaranteed performance, the proposed method will have strong industrial implications.

REFERENCES

[1] S. Kahne, "Pole-zero cancellation in SISO linear feedback systems," *IEEE Trans. Educ.*, vol. 33, pp. 240–243, Aug. 1990.
[2] B. C. Kuo, *Automatic Control Systems*, 7th ed. Englewood Cliffs, NJ: Prentice-Hall, 1995.
[3] K. J. Astrom and B. Wittenmark, *Computer Controlled Systems, Theory and Design*, ser. Information and Systems Science. Englewood Cliffs, NJ: Prentice-Hall, 1984.
[4] F. L. Lewis, *Applied Optimal Control and Estimation*, 1st ed. Englewood Cliffs, NJ: Prentice-Hall, 1992.
[5] A. L. Tits and Y. Yang, "Globally convergent algorithm for robust pole assignment by state feedback," *IEEE Trans. Automat. Contr.*, vol. 41, pp. 1432–1452, Oct. 1996.
[6] L. Yuan, L. E. K. Achenie, and W. Jiang, "Linear quadratic optimal feedback control for systems with poles in a specified region," *Int. J. Control.*, vol. 64, no. 6, pp. 1151–1164, Aug. 1996.
[7] R. N. Clarke, "Another reason to eschew pole-zero cancellation," *IEEE Contr. Syst. Mag.*, vol. 8, pp. 87–88, Apr. 1988.
[8] M. Nakamura, S. R. Munasinghe, S. Goto, and N. Kyura, "Enhanced contour control of SCARA robot under torque saturation constraint," *IEEE/ASME Trans. Mechatron.*, vol. 5, pp. 437–440, Dec. 2000.
[9] S. R. Munasinghe, M. Nakamura, S. Goto, S. Aoki, and N. Kyura, "High speed precise control of robot arms with assigned speed under torque constraint by trajectory generation in joint coordinates," in *Proc. IEEE Int. Conf. Systems, Man, and Cybernetics (SMC'99)*, Oct. 1999, pp. 854–859.
[10] S. R. Munasinghe, M. Nakamura, S. Goto, and N. Kyura, "Optimum contouring of industrial robot arms under assigned velocity and torque constraints," *IEEE Trans. Syst., Man, Cybern.*, vol. 31, pp. 159–167, May 2001.
[11] H. E. Jenkins and T. R. Kurfess, "Adoptive pole-zero cancellation in grinding force control," *IEEE Trans. Contr. Syst. Technol.*, vol. 7, pp. 363–370, May 1999.

[12] F. Ohkawa and Y. Yonezawa, "A discrete model reference adaptive control system for a plant with input amplitude constraints," *Int. J. Control*, vol. 36, no. 5, pp. 747–753, Nov. 1982.

[13] A. N. Payne, "Adaptive one-step-ahead control subject to an input-amplitude constraint," *Int. J. Control*, vol. 43, no. 4, pp. 1257–1269, Apr. 1986.

[14] C. Zhang and R. J. Evans, "Adaptive pole-assignment subject to saturation constraint," *Int. J. Control*, vol. 46, no. 4, pp. 1391–1398, Oct. 1987.

[15] D. Y. Abramovich and G. F. Franklin, "On the stability of adaptive pole-placement controllers with a saturating actuator," *IEEE Trans. Automat. Contr.*, vol. 35, pp. 303–306, Mar. 1990.

[16] C. Zhang, "Discrete-time saturation constrained adaptive pole assignment control," *IEEE Trans. Automat. Contr.*, vol. 38, pp. 1250–1254, Aug. 1993.

[17] A. R. Teel, "Semi-global stability of linear null controllable systems with input nonlinearities," *IEEE Trans. Automat. Contr.*, vol. 40, pp. 96–100, Jan. 1995.

[18] Z. Lin, A. Saberi, and A. A. Stoorvogel, "Semiglobal stabilization of linear discrete-time systems subject to input saturation via linear feedback—An ARE-based approach," *IEEE Trans. Automat. Contr.*, vol. 41, pp. 1203–2107, Aug. 1996.

[19] D. De Santis and A. Isidori, "On the output regulation for linear systems in the presence of input saturation," *IEEE Trans. Automat. Contr.*, vol. 46, pp. 156–160, Jan. 2001.

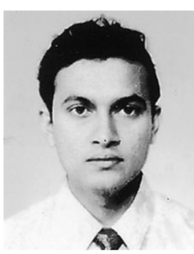
[20] M. Nakamura, S. Goto, and N. Kyura, *Mechatronic Servo System Control* (in Japanese) Morikita Shuppan, Tokyo, Japan, 1998.

[21] S. Goto, M. Nakamura, and N. Kyura, "Modified taught data method for industrial mechatronic servo-controller to achieve accurate contour control performance," presented at the IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics (AIM), Waseda Univ., Tokyo, Japan, June 1–4, 1997.

[22] F. Z. Chaoui, F. Giri, L. Dugard, J. M. Dion, and M. M'saad, "Adaptive tracking with saturating input and controller integral action," *IEEE Trans. Automat. Contr.*, vol. 43, pp. 1638–1643, Nov. 1998.

[23] C. H. An, "Experimental evaluation of feedforward and computed torque control," *IEEE Trans. Robot. Automat.*, vol. 5, pp. 368–373, June 1989.

[24] S. R. Munasinghe, M. Nakamura, S. Goto, and N. Kyura, "Precise control of industrial robot arms considering trajectory allowance under torque and speed constraints," in *Proc. IEEE Int. Conf. Robotics and Automation*, May 2001, pp. 3949–3954.



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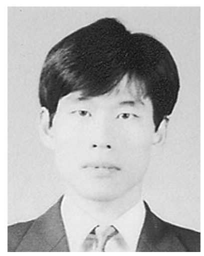

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