Redefinition of the Robot Motion-Control Problem

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ABSTRACT: The objective of this paper is a redefinition of the robot control problem, based on (1) realistic models for the industrial robot as a controlled plant, (2) end-effector trajectories consistent with manufacturing applications, and (3) the need for end-effector sensing to compensate for uncertainties inherent to most robotic manufacturing applications. Based on extensive analytical and experimental studies, robot dynamic models are presented that have been validated over the frequency range 0 to 50 Hz. These models exhibit a strong influence of drive system flexibility, producing lightly damped poles in the neighborhood of 8 Hz, 14 Hz, and 40 Hz, all unmodeled by the conventional rigid-body multiple-link robot dynamic approach. The models presented also quantify the significance of nonlinearities in the drive system, in addition to those well known in the linkage itself. Simulations of robot dynamics and motion controllers demonstrate that existing controls coupled with effective path planning produce dynamic path errors that are acceptable for most manufacturing applications. Major benefits are projected, with examples cited, for use of end-effector sensors for position, force, and process control.

Models of Robot Dynamics for Control System Design

Nearly all models for robot dynamics presented in the literature are based on the assumption that the arm is a linkage of connected rigid bodies [1]. Using the Newton-Euler, Lagrange, Kane, or other approaches, the kinematics and dynamics of multiple-link robot arms are derived and reduced to the following form:

\[ H(q)\ddot{q} + C(q, \dot{q}) + G(q) + K(q)^T M = T \]

(1)

In this equation, \( q \) is a vector of robot joint angles; \( H \) is a moment of inertia matrix; \( C \) is a vector specifying centrifugal and Coriolis effects; \( G \) is a vector specifying gravitational effects; \( K \) is a Jacobian matrix relating joint torques to \( M \), the vector of forces and moments applied to the end effector; and \( T \) is the vector of torques applied by the actuators at the drive points on each arm link. The plant so described may be viewed as a set of second-order differential equations, with cross-coupling and nonlinear effects resulting from dynamic interactions among the links of the robot arm. Equation (1) is necessary, but not sufficient, to represent the dominant dynamics of the plant, since it does not include very important interactions with the drive system.

Drive Systems with Mechanical Compliance

In much of the literature, the actuators providing the drive torques are modeled as pure torque sources, or as first-order lags. This assumption is the Achilles' heel of the class of robot dynamic models represented by Eq. (1). An intensive analytical and experimental study of robot control system modeling and design has been conducted by General Electric for a robot of the configuration shown in Fig. 1, which is representative of a large class of contemporary industrial arms [2]. The significance of drive system and mechanical compliance has been recognized in only a few prior papers [3], [4].

The robot is powered by electromechanical drives, consisting of DC or AC motors in series with a harmonic drive used for speed reduction. (A harmonic drive is a compact, high-torque, high-ratio, in-line gear mechanism incorporating a rigid "circular spline," an elliptical "wave generator," and a nonrigid "flex spline.".) The motors and harmonic drives are mounted on or near the base, with drive torques transmitted to the drive points on the arm links via mechanical links, such as bars or chains. The mounting of drive motors in this manner, in contrast with mounting at the joints, can be shown to provide superior dynamic characteristics [5].

The dynamic response of the integrated system consisting of the drive motor, harmonic drive, linkages, and arm may be measured experimentally by recording the motor current, motor velocity (tachometer feedback signal), and arm motion (integrated accelerometer signal) as the servo is excited with random or sinusoidal input signals. For a given (small) signal level, the drive system may be characterized by a linearized frequency response function. An example of such a frequency response function, computed through FFT analysis of signals recorded during random excitation testing, is shown in Fig. 2. The strong antiresonance phenomenon exhibited in Fig. 2 is typical of electromechanical drives, with compliance in series with the load, and is grossly divergent from the torque source or first-order lag representation of the drive system cited earlier. Although this behavior is well known by the industrial controls technical community, it has been ignored in much robotics research.

The existence of resonant behavior inside the robot motion-control loop has a dramatic impact on control system design, providing the motivation for development of the models described below. For example, one approach to improving robot motion-control performance is to decouple the dynamics of the robot links through nonlinear control [6]. The decoupling action performed by the controller is particularly significant in the same frequency range as the above resonant behavior. Decoupling controllers that do not take this strong resonance into account have little chance of successful implementation. Similarly, adaptive control is an alternative approach, proposed frequently [7], [8]; however, from adaptive control theory, it is known that "unmodeled dynamics," such as this drive system resonance, lead to severe stability and robustness problems. The existence of drive system interactions does not preclude future use of nonlinear or decou-
The dynamic modes of this system consist of an aperiodic “rigid-body” mode; a “torsional” mode, in which the motor inertia oscillates against the combined inertia of the base and arm; a “sway” mode, in which the predominant motion is a lateral oscillation of the forearm; and a “yaw” mode, in which the forearm oscillates about a vertical axis. The torsional mode is responsible for the resonance at 9.6 Hz in Fig. 2; the sway and yaw modes give rise to the resonances at 14 Hz and 40 Hz [2].

The sway and yaw modes are not significantly excited by motor inputs, so that for the frequency bandwidth of interest for position control (10 Hz, say), perhaps only the rigid-body and torsional modes are of concern, and a simplified two-inertia model could be used for control design purposes. However, it should be noted that both of the higher frequency “structural” modes could be excited by forces arising from tool/workpiece contact or from inertia forces generated by wrist motions. In some configurations, the sway mode could be excited by Coriolis forces arising from upper-arm and forearm motions. The mechanics of the “structural” modes are considered further later in this paper.

Assuming linear elements for the model of Fig. 3, and combining the base and arm inertias into one inertia $J_1$ (referred to as the motor shaft speed), a transfer function model may be derived that accounts for the magnitude and phase characteristics presented in Fig. 2. For a high-current servo-loop gain and small armature inductance, the transfer function between motor torque and current command is essentially a pure gain $K_i$, where $K_i$ is the control (10 Hz, say), perhaps only the rigid-body and torsional modes are of concern, and a simplified two-inertia model could be used for control design purposes. However, it should be noted that both of the higher frequency “structural” modes could be excited by forces arising from tool/workpiece contact or from inertia forces generated by wrist motions. In some configurations, the sway mode could be excited by Coriolis forces arising from upper-arm and forearm motions. The mechanics of the “structural” modes are considered further later in this paper.

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$$\begin{bmatrix} W_m \\ W_l \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} I_c \\ -T_l \end{bmatrix}$$

where

$$M_{11} = K_i (J_1 s^2 + (B_1 + c)s + k)/D!$$
$$M_{21} = K_i (c s + k)/D!$$
$$M_{12} = (c s + k)/D!$$
$$M_{22} = (J_m s^2 + (B_m + c)s + k)/D!$$
$$D! = J_m J_1 s^3$$

$$+ [J_m (B_1 + c) + J_1 (B_m + c)] s^2$$
$$+ [k (J_m + J_1) + B_m B_1$$
$$+ c (B_m + B_1)] s$$
$$+ k (B_m + B_1)$$

Using component data or experimentally identified parameters for the motor and drive system, the desired drive system model to be
used in control system design may be developed for various motion amplitude levels. Using the shorthand notation

$$K(a)[z, w]$$

to represent

$$K(s/a + 1)\left(\frac{(s/w)^2 + 2(z/s/w) + 1}{(s/w)^2 + 2(z/s/w) + 1}\right)$$

the transfer functions appropriate to the data in Fig. 2 become

$$\begin{bmatrix} W_m \\ W_i \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} I_c \\ -T_i \end{bmatrix}$$

where

$$M_{11} = 26.7[0.10, 44.7]/D!$$

$$M_{21} = 26.7(222)/D!$$

$$M_{12} = 66.7[222]/D!$$

$$M_{22} = 66.7[0.52, 44.7]/D!$$

$$D! = (20.7)[0.29, 60.1]$$

Evaluating the transfer function for $$W_m/I_c$$ gives the "model" Bode plot in Fig. 2, which compares favorably with the experimental data. Similarly, close agreement is obtained for load velocity in response to current command, with the experimental data measured as velocity at the robot wrist.

The dynamic modes of the open-loop servo displayed in Eq. (3) consist of the aperiodic "rigid-body" mode, with a time-constant of approximately 1/20.7 = 48 ms, the "torsional" mode with a natural frequency of about 60 rad/s, and a damping ratio of about 0.3.

Nonlinearities in the robot arm and drive systems produce changes in the linearized control model gains and pole locations. Configuration and payload changes can each produce two-fold variations in the referred load inertia $$J_l$$. From Eq. (2), it can be seen that the natural frequency and damping ratio of the zero in the $$W_i/I_c$$ transfer function will correspondingly vary inversely with $$J_l$$. The natural frequency of the torsional mode depends in the same way on the effective inertia $$J_{eff} = J_a + J_l/2$$ rather than $$J_a$$. A large part of the energy dissipation, represented by the effective viscous damping coefficients in Eq. (2), arises in fact from Coulomb friction, so that both the DC gain (which is inversely proportional to the total external damping $$B_m + B_i$$) and the damping ratios of the poles and zeroes vary widely with motion amplitude; gain variations of 300 percent and damping ratios as low as 5 percent of critical have been observed. The variation of natural frequency with amplitude, due to the nonlinear hardening spring characteristic, can be as much as 40 percent.

The twist and bend axes of the robot (located at the wrist) do not exhibit the previously described resonant behavior in the frequency range below 50 Hz. The harmonic drive output of the wrist bend motor is coupled to the bend axis by a chain-rod arrangement. The chains are likely to add considerable absolute damping to the "load" in a two-inertia model for the bend axis. Also, the load inertia referred to the motor shaft is considerably smaller than the motor inertia, in contrast to the rotation axis case where these two inertias are of similar magnitude. The result of these effects is to increase both the antiresonance and resonance frequencies and bring them very close together so that, with the increased damping, no resonance is observed.

Again, the nonlinear friction causes substantial changes in the gain and bandwidth of this system as the motion amplitude changes: the effective viscous damping may vary by a factor of five or more.

Dynamics of Articulated Manipulators

It is generally assumed that it is necessary for high-performance robot motion controls to compensate for the nonlinear, cross-coupled dynamics of articulated manipulator arms, as represented by Eq. (1). This assumption is often based, however, on examination of the form of the equations, without regard to the magnitudes of the nonlinear, cross-coupling terms in relation to the dominant dynamics of individual axis. Belief in this assumption was reinforced by experience of early robotics researchers with arm designs that are now obsolete, such as the Stanford arm.

A detailed examination of the behavior of contemporary manipulators, such as illustrated in Fig. 1, reveals a contrasting perspective: the dominant behavior of the arm is represented by decoupled models for each motor and drive unit. In a sense, the articulated arm of Fig. 1 has characteristics similar to those of a Cartesian robot. There are a number of factors that lead to this conclusion:

- The design of the arm, in terms of the mass distribution of its links and motor locations, inherently minimizes cross-coupling effects. This conclusion has been derived analytically [10], and has been verified through simulation by the authors.
- The high-gear ratios employed in most drive units cause the torques resulting from cross-coupling effects as reflected back to the motors to be minimal.
- Realistic limitations on motor torques prevent the arm from reaching velocities of sufficient magnitude for cross-coupling terms to become significant.
- As illustrated in the next section of this paper, realistic trajectories for robot arms in actual manufacturing applications rarely require extremes of velocity and acceleration.

Robots exhibiting this "Cartesian-like" behavior are increasing their penetration of the robot market in most manufacturing applications. This suggests that in the future, motion controls designed to compensate for cross-coupling effects will have rather limited benefit in terms of realized performance gains.

Nonlinearities in Robot Arm and Drive Systems

Nonlinearities associated with robot arm geometry and dynamic interactions among the arm links have been long recognized as important to the design of motion controls. In addition to robot arm nonlinearities, nonlinear characteristics of elements in the drive system play an important role in robot control system design.

The structure of the nonlinear model is shown in Fig. 4. Principal nonlinearities include:

(a) Stiffening spring characteristic of the harmonic drive.

(b) Viscous plus Coulomb friction damping for both the motor and load inertias.

(c) Current limiters in the motor control loops.

Backlash effects were found to be negligible in the drive systems studied.

Parametric values needed to characterize these nonlinearities were determined through direct experimental measurement or through parameter identification techniques [9]. The validity of the nonlinear model is tested by comparison of the magnitude and phase data measured under constant sinusoidal input testing with model predictions (Fig. 5). As signal level increases, there is a decrease in damping of the closed-loop poles of the
Fig. 4. Nonlinear model for robot drive system, including stiffening spring for harmonic drive, viscous plus Coulomb friction damping on both motor and load inertias, and motor torque limiting.

Fig. 5. Comparison of nonlinear drive system model and measured sinusoidal input describing functions $G(j\omega; a)$ for constant input amplitudes. Input amplitude is expressed as percent of torque limits on drive motors [9].

equivalent linear system, a slight increase in the frequency of these poles, and a decrease in loop gain at higher frequencies.

From a control design point of view, the current (torque) limiter is the most significant nonlinearity. By replacing the stiffening spring and Coulomb friction nonlinearities with equivalent linear terms (using an SIDF approach), a simplified nonlinear model for the drive system results that closely corresponds with the measured nonlinear behavior. However, for time-domain simulations, it is necessary to include all the above nonlinearities to obtain good agreement with measured robot motions for both small and large amplitude motions.

Motion-Control Performance Requirements

The performance of motion controls is best evaluated in the context of requirements during manufacturing applications. In this section, we describe the results of simulations of robot dynamics and motion controls for two representative cases.

Simulation of Motion-Control Performance

Realistic simulations of robot dynamic response have been developed and validated experimentally for each of the major components that comprise the combined robot arm and controller system. Principal elements in the simulation shown schematically in Fig. 6 include:

- Kinematics and dynamics of the multiple-link robot arm, consisting of revolute and prismatic joints.
- Models for the robot drive systems, including current-limited DC motors, harmonic drives, and inertia and flexibility
Two case studies of manufacturing applications of robots were conducted by General Electric by linking a powerful off-line programming facility for deceleration coming into the corner point; as shown in Fig. 8b, the overshoot is reduced to 1.5 mm. The conclusion here is that effective trajectory planning is useful, if not essential, to meeting specifications for dynamic path accuracy.

Feedback Using End-Effector Sensing

Sources of Errors in Manufacturing

The most significant control problem to be solved in robotics is the use of sensor information to compensate for uncertainties in manufacturing processes. Most present robot controllers are limited in functionality to repetitive motion sequences, with limited or no

![Diagram of P50 Dynamic Simulation](image)

Fig. 6. Structure of integrated robot and drive system dynamic simulation model.

effects in the mechanical elements connecting motors to arm links.
- Digital controls for individual joint servo loops, including finite sampling rate and amplitude quantization effects. The finite sampling rate results from throughput constraints on the microprocessors used in the servo control, while amplitude quantization results from finite resolution of encoders sensing joint angles.
- Algorithms used for coordinate transformations, path interpolations, and special programming features, such as rough positioning, dwells, and smooth decelerations.

Requirements for Manufacturing Applications

Two case studies of manufacturing applications of robots were conducted by General Electric by linking a powerful off-line programming CAD system with the dynamic simulation described above [10]. The purpose of these case studies was to determine the extent to which dynamic errors in robot motion control were significant in realizing the potential benefits of robotic automation, and to identify areas for greatest benefit through improved motion controls.

The first case study considered use of the robot in Fig. 1 for arc welding, one of the most prevalent current applications for robotics. Welding speeds were considered up to 2.5 cm/sec (60 in/min), typical for MIG welding. For this case, dynamic errors introduced at these speeds were found not to be significant.

The second case study involved the testing of circuit boards in a test slot (Fig. 7). The robot extracts a board from a storage rack, inserts it into a slot for testing, and returns the board to the rack. The prime consideration for this study is the amount of clearance that the board has for entrance into the test slot.

The storage rack, containing six upright circuit boards, is located within the robot's reach. The test slot is located in a piece of test equipment that is not shown, and the center of the slot is located radially to the robot base. The slot is located parallel to the floor and can be entered when the wrist has a pitch and twist of zero degrees. The clearance for the board for entry into the test slot is 1.6 mm in width and height. The path error must be minimized to avoid damaging the circuit boards or the test slot.

The task was simulated as follows:

i. Move from the home position to approach the first board at high velocity.
ii. Grip the board.
iii. Slowly lift the board from the storage rack.
iv. Rotate the board and move to the front of the test station slot at high velocity.
v. Insert the board into the 10.2-cm-deep slot.
vi. Extract the board from the slot.
vii. Return the board to the rack.

viii. Index to the next slot in the rack and repeat for the rest of the boards, removing and inserting them by a combination of vertical and horizontal movements to avoid colliding with the previously tested boards.

A close-up view of the first board pickup is shown in Fig. 8a. The static error is due to deflection under gravity. The 8-mm peak-to-peak oscillation in the Y direction illustrates the maximum magnitude overshoot that can be produced by a step change in the programmed path.

There is a temptation to assume that improved motion controls could easily reduce the magnitude of this overshoot. However, when the flexibility in the drive system and torque limits on the motor are considered, plus the location of the feedback encoders on the motor (in contrast to end-effector sensing), prospects are far less optimistic. An alternative approach is to use the robot programming facility for deceleration coming into the corner point; as shown in Fig. 8b, the overshoot is reduced to 1.5 mm. The conclusion here is that effective trajectory planning is useful, if not essential, to meeting specifications for dynamic path accuracy.

![Diagram of Circuit Board Pick and Place Task](image)

Fig. 7. Simulation of circuit board pick and place task, with superimposed programmed and dynamic simulation paths [10].
capability for adaptive path modification to properly align the end effector with the workpiece. Stated another way, if advanced motion controls increase peak robot speeds by 100 percent (unlikely, due to motor torque constraints) without adaptive path modification, the resulting increase in use of robots in manufacturing will be marginal. Only in assembly applications is it likely that increased speeds alone will measurably change bot's in manufacturing will be marginal. Only in assembly applications is it likely that increased speeds alone will measurably change

Position Sensor Feedback

The most direct approach to the correction of robot motions to accommodate manufacturing process errors is through direct measurement and feedback of the position of the end effector relative to the workpiece. Note that although there is frequent discussion of absolute end-effector position sensing in the literature, this expensive technology will have limited benefit without simultaneous measurement of workpiece geometry. In contrast, a number of relatively inexpensive sensors are available or being developed that can measure the relative distance to the workpiece using optical, eddy current, or other means.

The architecture of a typical robot control without end-effector sensor feedback is shown in Fig. 9a [11]. The motion processor computes the desired path trajectory, coordinate transforms, and interpolation functions, sending joint commands to the axis control. The latter closes position loops around each of the joints in the arm. In contrast, the structure for position sensor feedback is shown in Fig. 9b, with feedback of the position error back to the motion processor that computes the desired robot trajectory. A detailed evaluation of the performance of this type of feedback structure has been published previously [11].

An excellent example of position sensor feedback is the use of optical joint trackers in robotic arc welding. Figure 10 shows the structure of the motion control for joint tracking in the General Electric TIG Welding Vision System [12], [13].

Contact-Force Sensor Feedback

In manufacturing applications such as assembly and deburring, control of contact forces between the end effector and workpiece is the principal objective [14]. Generally, bandwidth requirements for force control are higher than for position control. Since feedback through the motion processor, as shown in Fig. 9b, does not provide adequate bandwidth, the structure in Fig. 9c is employed with direct feedback of force signals to the controls of each axis loop.

Manufacturing Process Sensor Feedback

In some cases, robot motion control is not an end in itself, but provides an input to a complex manufacturing process. Again, we cite arc welding as an example, where arc current, wire feed rate, arc gap, torch velocity, and torch position all interact in producing a weld seam. The schematic for the robotic welding cell in Fig. 11 demonstrates the complexity of coordinating motion and process controls. Since the ultimate objective of a robotic arc welding cell is assurance of consistent, high-quality weld seams, robot motions must be controlled using

Fig. 8. Close-up view of dynamic error in circuit board pick and place task. Reduced overshoot using programmed deceleration at corner in (b) compared to no deceleration in (a) [10].

Fig. 9. Structures for end-effector sensor feedback control: (a) basic robot motion control, (b) sensor feedback to motion processor, and (c) sensor feedback to axis control [11].
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Fig. 10. Welding torch motion control for joint tracking and puddle centering (from Baheti et al., 1984).

Fig. 11. Schematic of robotic TIG welding vision system, including coordinated part positioner, wire feed controller, arc power supply, and joint tracking [13].

strategies that are complementary with manufacturing process variables. For example, feedback of measured weld puddle geometry, puddle position, and arc voltage to robot motion-control loops has been demonstrated by General Electric for the TIG welding process [12], [13].

Redefinition of the Robot Motion-Control Problem

The following summary of research reviewed in this paper is intended to serve as a redefinition of the robot motion-control problem.

Models for Control System Design

- Drive system flexibility plays a critical role in robot motion-control design. Fourth-order dynamic models exhibiting resonance/antiresonance behavior accurately represent the interaction of the drives with arm links. Wrist drive systems can often be represented with simpler, nonresonant models.
- Modern designs for articulated arms exhibit behavior that is "Cartesian-like," in that the effects of nonlinear cross-coupling terms are minimal. This permits more direct design of motion controls assuming decoupled axes for the robot.
- Torque limits on the motors and drives present the most significant nonlinearities in the motion-control problem.

Motion-Control Performance Requirements

- Most manufacturing applications employ robot end-effector trajectories that do not produce excessive dynamic path errors.
- In most cases, dynamic overshoot errors that do occur in the robot path are reduced to acceptable levels easily through programmed decelerations in the motion program, with minor penalty in total cycle time.
- The most significant factor constraining robot performance is motor torque limits. This underscores the importance of development of strategies for optimal path planning within the bounds of motor output.

Feedback Using End-Effecter Sensing

- Use of end-effector sensing to provide robot motion controls with intelligence capable of compensating for uncertainties in manufacturing has enormous potential for expanding the scope of robot applications.
- Different feedback structures may be used for control of end-effector position, contact force with the workpiece, or the manufacturing process itself, depending on the bandwidth requirements of the closed-loop system.

References

Conference Calendar

Montana Summer Institute on Current Issues in Adaptive Control, Aug. 21–27, 1985, Montana State University, Bozeman, Montana. Contact: Deena Westfall, Electrical Engineering Department, Montana State University, Bozeman, MT 59717, phone: (406) 994-2505.


1st IFAC Symp. Robot Cont., Nov. 6–8, 1985, Barcelona, Spain. Contact: Prof. G. Ferrate, Polytechnic Univ. of Barcelona, Via Augusta 242, Barcelona, Spain.


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