TRAJECTORY CONTROL OF INDUSTRIAL ROBOTS

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ABSTRACT

Trajectory control has been an area of active research over the past decade and numerous control strategies have been proposed. Generally speaking, industrial robots have not yet reached the stage where they performed trajectory tracking tasks satisfactorily. Characteristics inherent to the nature of a Typical manipulator design make the implementation of proposed control strategies difficult. In this paper, two strategies proposed for the trajectory control of robots are reviewed, and are explained the difficulties associated with their implementation.

INTRODUCTION

Manipulation robots are used widely in industry to perform a variety of tasks. Common examples are palletising, machine loading, and spot welding. We classify these tasks as 'pick-and-place' activities. In 'pick-and-place' operations the robot is required to move its end-effector from a location A to some other location B. The route taken in moving from A to B should be such that the cycle time is minimised, however provided collisions do not occur small derivation from the planned route are of little or no consequence. Most popular contemporary industrial robots, such as the Puma 600 or the Cincinnati Milacron T3-726 (Figure 1.), are designed to performed 'pick-and-place' operations. For other tasks such as seam tracking in arc welding, ultrasonic or electromagnetic contour inspection, laser and water cutting, and glue laying it is often essential that the end-effector follows the planned trajectory has to be accurately followed as a function of time,. This spatial-temporal problem is known as the trajectory control problem.

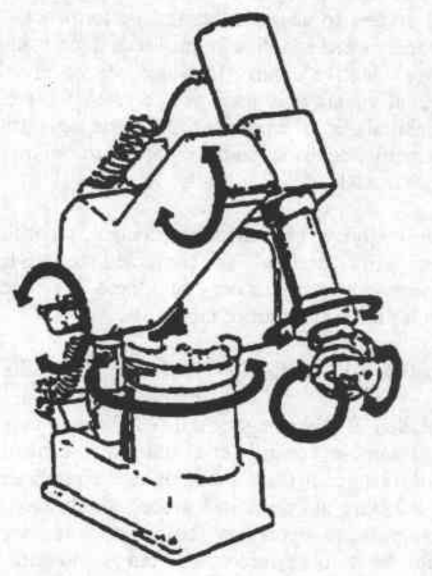
The general objective of trajectory control is to make the actual motion (ie, its instantaneous position, velocity and acceleration) of the robots end-effector (hand or wrist) match the desired motion. The desired motion is usually determined by a higher level trajectory planner which is not considered part of the control system.

The features we seek in a trajectory control strategy are

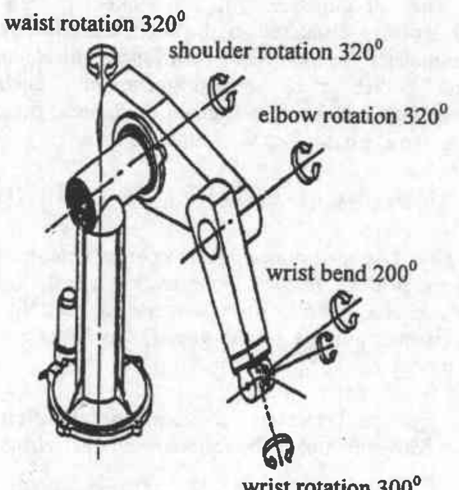
i. that it achieves very accurate tracking,

ii. that it rejects or accommodate abroad class of disturbances,

iii. that it accomplishes the above features with minimal complexity and maximal reliability.



a. Cincinatti Milacron T3-726.



b. Unimation PUMA 600.
Figure 1. Examples of Industrial Robots.

AVAILABLE CONTROL TECHNIQUES

The three most common techniques proposed to meet these ends are variable structure control, adaptive control, and torque-force. In the generalised case of variable structure control, the state-space is partitioned into several regions that are bounded by a space trajectory conformal to linear behaviour. An appropriate control law is assigned to each region in the partitioned space. If the end-effector deviates from its proper trajectory and enters a particular region of the state space, the appropriate control law drives it back on path.

In adaptive control techniques, the controller parameters are changed in real time to allow the control system to adapt to desired performance. The most widely cited adaptive control technique is model reference adaptive control in which a time invariant differential equation is used as the reference model. The manipulator is controlled by adjusting position and velocity feedback gains in order to follow the reference model.

The majority of trajectory control algorithms, however are classified as computed torque-force techniques. A discussion of these techniques constitutes the major part of this paper.

TORQUE-FORCE CONTROL STRATEGIES

Included in this category are feedforward control, resolved motion control, and non-linear control. A common feature of these methods is the requirement for an accurate mathematical model which describes the manipulators dynamics. This model is used to compute the torques-forces required to produce the desired motion.

The formulation of dynamic models is exhaustively discussed in the literature. Usually the manipulator is assumed to be a linkage of connected rigid bodies and standard techniques, such as Langrange and Newton-Euler formulations, are used to arrive at a model; of the following form

$$T = J(q)\ddot{q} + b(q,\dot{q}) + g(q) + f(q,\dot{q}) \qquad (1)$$

Where **T** is an **n** dimensional vector of joint torques-forces, **q** is the vector of joint angles, **J** is the **n** by **n** link inertia matrix, **b** the vector of Coriolis and centripetal, **g** is the gravity vector, and **f** the vector of frictional terms.

Equation 1represents **n** second order differential equations which have the following characteristics:

- They are highly non-linear.
- The link inertias reflected to the actuators depend on the robot arm configuration and the payload.
- There is cross coupling of the differential equations due to Coriolis and centripetal effects, frictional effects, and inertia forces.

Torque-force control strategies take into account the dynamic coupling and non-linearities in robotic manipulators by linearising Equation 1 about a given state allowing the application of linear feedback. To see how this is done we will consider two specific algorithms; one using feedforward control, and the other using resolved motion control.

FEED-FORWARD CONTROL

In feed-forward control the desired joint motions $(q, \dot{q}, \ddot{q}\ )$ are used to compute the gross torques to be applied to the actuator. These torques are calculated 'off-line' using the dynamic model (Equation 1) of the manipulator.

Figure 2 is a schematic representation of a feedforward controller proposed by An et al. [3]. The controller uses a hybrid of feedforward control and independent joint PD feedback control. The PD control is described

$$T_{PD} = K_v(\dot{q}_d - \dot{q}) + K_p(q_d - q) \qquad (2)$$

Where q and q are desired joint velocities and angles and K and K are n by n diagonal matrices for position and velocity gain. Gross torques, calculated of-line, are given

$$T_{ff} = J_c(q_d)\ddot{q}_d + b_c(q_d, \dot{q}_d) + g_c(q_d) + f(q_d, \dot{q}_d) \qquad (3)$$

Where the subscript c refers to computed values. When this equation is combined with Equation 2 the result is

$$T = T_{ff} + K_v(\dot{q}_d - \dot{q}) + K_p(q_d - q) \qquad (4)$$

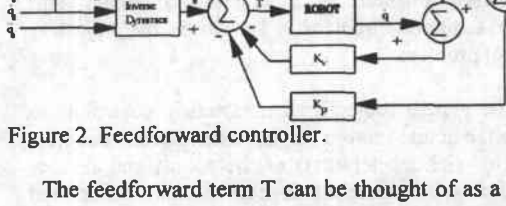


Figure 2. Feedforward controller.

The feedforward term T can be thought of as a set of nominal torques which linearise Equation 1 about a particular operating point q, q, q . This allows us to use linear feedback terms whilst still maintaining stability. The control system is not unconditionally stable so the choice of elements for K an K must be judicious. The notion of T being computed off-line is quite acceptable since the computation is a function of desired values only.

RESOLVED MOTION CONTROL

In resolved motion control comparison of the actual and desired motion drives the torque computations. In this instance the dynamics is computed "n-line" Luh et al. [1] suggested the resolved acceleration control system shown in Figure 3.

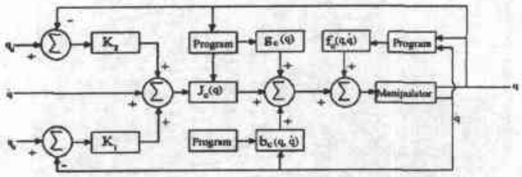


Figure 3. Resolved acceleration control.

The control equation is

$$T_{ct} = J(q)\ddot{q}^{*} + b(q,\dot{q}) + g(q) + f(q,\dot{q}) \quad (5)$$

Where;

$$\ddot{q}^{*} = \ddot{q}_d + K_1(\dot{q}_d - \dot{q}) + K_2(q_d - q) \quad (6)$$

And K and K are diagonal scalar gain constant matrices. If the computed elements are exactly equivalent to their actual counterparts, then Equation 5 becomes

$$T = J(q)(\ddot{q}_d + K_1(\dot{q}_d - \dot{q}) + K_2(q_d - q)) + b(q,\dot{q}) + g(q) + f(q,\dot{q}) \quad (7)$$

Equating Equation 1 and 7 gives

$$J(q)(\ddot{q}_d + K_1(\dot{q}_d - \dot{q}) + K_2(q_d - q)) = 0 \quad (8)$$

If J(q) is non-singular and we let e be the joint position error, Equation 8 becomes

$$\ddot{e}_q + K_1\dot{e}_q + K_2 e_q = 0 \quad (9)$$

Provided that the dynamic model is correct, the strategy will produce a stable response if the characteristic roots of Equation 9 lie to the left of the imaginary axis. If these roots happen to be both negative and real, the error, e, will approach zero asymptotically. This is a favourable situation. The choice of the elements in K and K thus determine the systems stability and performance.

IMPLEMENTATION OF TRAJECTORY CONTROL ALGORITHMS

As noted earlier very few of the proposed trajectory control algorithms have been implemented on actual industrial robots. Most papers present results based on computer simulations. This lack of experimental evidence makes it difficult to determine how good or practical the various algorithms, such as the two presented here, are.

The difficulties associated with successful implementation can be directly related to the mechanical design of industrial robots. Typical industrial manipulators such as the PUMA series or the Cincinnati Milacron T3-726, have small actuators at the joints and utilise large gear ratios to enable them to exert enough torque on the links. This arrangement introduces significant (undesirable) non-linearities such as friction and backlash at the joints. An [2] found that friction terms account for approximately 50% of the motor torques for the PUMA 600 manipulator at MIT.

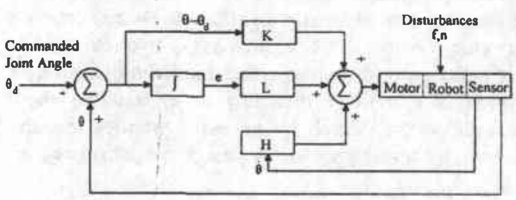


Figure 4. Independent PID joint control.

Since these non-ideal effects are extremely difficult to model mathematically, most of the proposed control algorithms are based on the rigid body dynamic model of the robot neglecting non-ideal characteristics. Ironically, the effects of the rigid body dynamics are relatively small for highly geared manipulators, since inertias reflected through the gear train are reduced by the square of the gear ratio. The CMT3-726, for example, has a trunk gear ratio of 96:1. Hunter [6] found that the rigid body inertia for the arm varies (approximately) between 7.5 kgm^2 and 8.5 kgm^2 depending on the arm configuration, thus the maximum inertial load seen by the trunk actuator, due to the rigid body dynamic effects is

$$I_{act}(max) = 8.5/(96)^2 = 9.2*10^{-4} kgm^2 \quad (10)$$

The inertia of the actuator rotor is $1.4*10^{-3}$ kgm^2, or about the same as the arms reflected rigid body inertia. With frictional effects requiring as much as 50% of the actuator torque, rigid body effects are swamped by the combined rotor inertia load and friction load. Thus, using highly geared drives effectively decouples the dynamics of the manipulator. This is the reason why most commercial industrial manipulators use independent PID joint control (Figure 4).

We have established that rigid body effects constitute only a fraction of the inertial load seen by the actuators. This does not mean not mean that the dynamics of the arm have no effect on end-effector motion. If this were the case PID control would be a simple an effective means of achieving trajectory control. To see how the tracking performance of a commercial manipulator is influenced by its own dynamic behaviour, consider Figure 5 taken from [6], which shows the results of an experiment in which the end-effector of a CMT3-726 manipulator was commanded to move around a 25mm square. As can be seen there is significant deviation between the planned trajectory and the actual trajectory. The Figure 5 also illustrates how tracking performance diminishes with increasing speed.

The deviation of the actual trajectory from the planned trajectory is due to drive system compliance and arm-link flexibility. Neither of these 'non-ideal' effects is included in the rigid body model (Equation 1), yet they are obviously significant. To implement a trajectory control strategy, such as the two reviewed in this paper, would require either modelling the effects (which is extremely difficult) or eliminating them through design (which by necessity implies that the philosophy underlying robot design be considered an initio).

It has been suggested [6] that more realistic dynamic models can be developed experimentally using modal analysis and associated parameter extraction techniques. There is much merit to this approach, however, to date there is little evidence of control systems, based on such models, being implemented. Indeed to find examples of implementation we must turn our attention away from industrial robots towards experimental robots, such as the MIT direct drive arm.

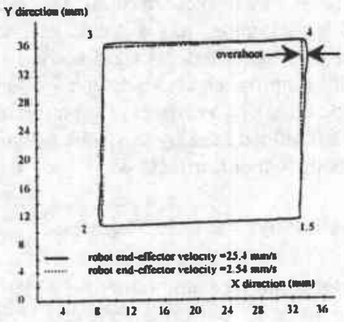


Figure 5. Influence of Unmodelled dynamics on Tracking performance.

DIRECT DRIVE TECHNOLOGY

To conclude, the work done in the Artificial Intelligence Laboratory at MIT [2] will be reviewed. Using direct drive technology they have been able to eliminate many of the non-ideal dynamic effects, which limit the performance of contemporary design. Figure 6 shows the direct drive arm.

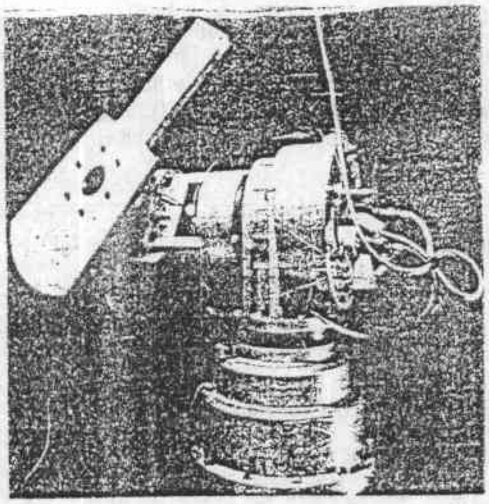


Figure 6. Direct Drive Arm.

Since the links are directly coupled to the motors, backlash effects are eliminated and joint frictional effects are reduced immensely. Therefore, the dynamics of direct drive arms can be modelled accurately by rigid body formulations. This makes these arms not only more suitable for the type of control strategies discussed in this paper, but also it makes it necessary to use such control algorithms since the full coupled dynamics of the links are reflected directly to the actuators.

Using this arrangement brings some serious disadvantages. Since there is no gearing, the motors have to be large enough to expert necessary torques. This makes the manipulator large and more difficult to control. Also, since the motors must exert large torques, large currents flow through the winnings, overheating the motors quickly. Despite these drawbacks the ability to model these manipulators using ideal rigid body dynamics makes them very attractive for trajectory control applications. As the price of the rare earth permanent magnet DC motors used to actuate the arm decreases, direct drive arms are certain to find application in industrial environments.

Figure 7 shows the results of an experiment by An [2] designed to compare feedforward control, resolved motion control and PD control when implemented on the direct drive arm robot. In the experiment the end-effector was commanded to follow a path defined by a fifth order polynominal. The graphs show the joint angle error for each actuator as a function of time.

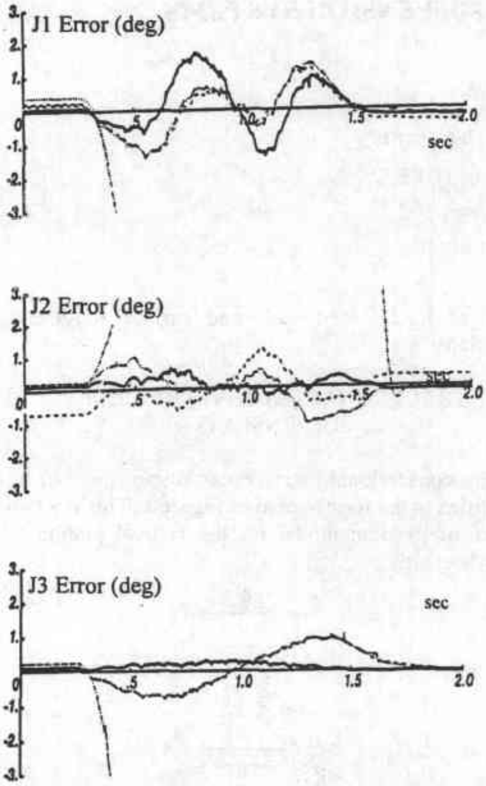


Figure 7. Comparison of Control Strategies.

The feedforward and resolved motion controllers both show a significant reduction in tracking errors compared with PD control, especially for the first two joints. The relatively poor performance of the third joint is attributed to poor estimates of the link inertia and friction in the drive. It is difficult to interpret these results in the broader context of end-effector motion, however the author states that 'dynamic compensation using either feedforward and resolved motion control improves trajectory accuracy significantly".

CONCLUSION

In this Paper, two strategies proposed for the trajectory control of robots were reviewed, and have been attempted to explain the difficulties associated with their implementation. Some emphasis has been placed on the use of direct drive arms to overcome these difficulties. This does not mean that accurate trajectory control can only be achieved through the use of direct drive arms. Rather, my point of emphasis is that to control a robots trajectory accurately a realistic dynamic model is essential. If we can develop such model models then the trajectory control of any robot arm using strategies such as those mentioned will be possible.

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