ON THE CONTROL OF ROBOTIC MANIPULATORS

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SUMMARY: The motion of robotic manipulators is controlled by actuators driving the joints of the manipulator. The actuators can be electrical, hydraulic or pneumatic. A brief account is given of the different types of actuators. The main issues regarding the control of robotic manipulators are summarized. Also, a selective literature survey of the topic is given.

Key Words: Link, manipulator, robot.

INTRODUCTION

The motion of robotic manipulators is controlled by actuators that drive the joints of the manipulator. The actuators can be electrical, hydraulic or pneumatic. In the following sections, we give a brief account of the different types of actuators and we summarize the main issues regarding the control of robotic manipulators.

ELECTRICAL ACTUATORS

The most widely used electrical actuators are stepper motors and DC motors. The DC motor has two wire windings; one wrapped around the rotating armature (armature circuit) and the other wrapped around a fixed rotor (field circuit) that produces a steady magnetic field. The motion of the motor can be controlled through either the current in the armature winding (armature control) or the current in the field winding (field control). Figure 1 shows the equivalent circuit for a DC motor.

The motor torque T_m is related to the armature current I_a and field current I_f by

$$T_m = KI_a I_f$$

where K is a constant.

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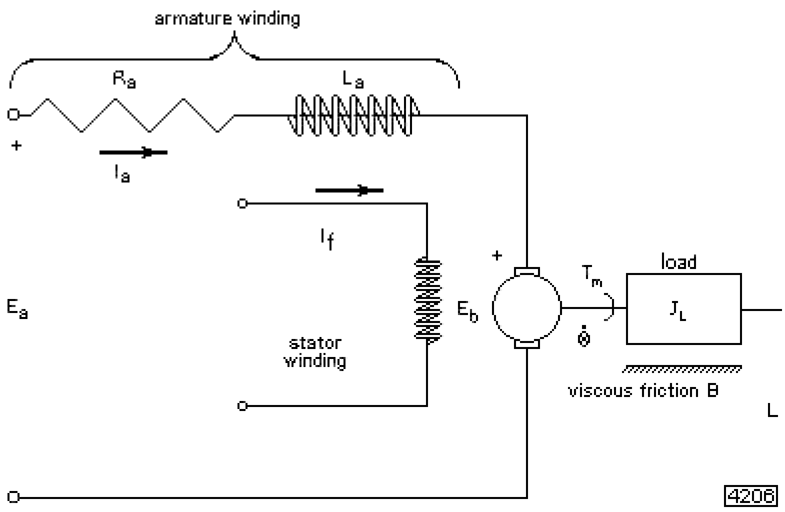
In armature control, the field current I_f is kept constant and T_m is controlled by varying the armature current I_a. This type of control is more popular since it allows the speed to vary in a wider range than in the case of field control, where I_a kept constant and T_m is varied by varying I_f.

A stepper motor is a DC motor that accepts a pulse or digital input and rotates in discrete steps. It is used as a positioning device where the shaft angle can be positioned at one of a finite number of pre-specified discrete angles. With the increasing use of digital computers in robotic control, stepper motors are becoming increasingly popular, although their torque output is rather limited.

HYDRAULIC ACTUATORS

Hydraulic actuators, pump an incompressible fluid and use the resulting pressure to drive a mechanical load. Figure 2 shows an example of a hydraulic actuator. In the shown system, the pump produces a pressure differential around the piston by controlling the direction of the flow, causing the piston to move in the desired direction.

Figure 1: Separately excited DC motor.



Hydraulic actuators are more common in applications requiring high power. Their main disadvantage is that they exhibit highly nonlinear behavior due to the compressibility of the fluid and due to the leakage losses. A linear model is possible only under restricted conditions. Some advantages of hydraulic actuators, in addition to the high power capability, are their higher accuracy, better frequency response, smooth performance at low speeds as well as their self-cooling nature.

PNEUMATIC ACTUATORS

In pneumatic actuators, a compressible fluid (air) is used to drive a piston. Their main advantage is simplicity and thus they are ideal for grippers. Other advantages are high speed, low cost, simple control and cleanness. Their main disadvantage is time delay, due to the compressibility of the fluid. The propagation delay in a pneumatic system is about four times greater than in a hydraulic system.

STATE-SPACE REPRESENTATION OF DYNAMIC EQUATIONS FOR A ROBOT MANIPULATOR

The dynamic equations of a robot manipulator are differential equations in which time appears as an independent variable. These equations can be represented in the form of a vector, a first-order differential equation of the form.

$$x = f\,(x(t), u(t)) \qquad \text{(A2)}$$

where x is a state vector, u(t) is an input to the system, and f is a differentiable, vector-valued function.

For an n-jointed serial link, x is a 2n-dimensional vector whose components are positions and velocities of the joints. In general, the function f is highly nonlinear and cannot be easily solved in closed form. Instead, digital computer simulation is used. This is accomplished by approximating Eq. (A2) by a vector, a difference equation of the form

$$x\,((k+1)T) = g\,(x(kT), u(kT)) \qquad \text{(A3)}$$

where T is the sampling period and g is a vector-valued function related to f.

Another approach is to linearize Eq. (A2). This can be accomplished by using perturbation methods or by using feedback and/or feed forward loops (1). The resulting linearized equation has the for

$$= A\,x\,(t) + B\,u\,(t) \qquad \text{(A4)}$$

$$y\,(t) = C\,x\,(t) \qquad \text{(A5)}$$

where A, B and C are matrices and y(t) is the output vector, usually representing the position and orientation of the end-effector.

Having a linear model, all linear control methods can be used. In particular, the stability and controllability of the model can be studied. The linear model in Eq. (A4) can also be discretized for digital computer simulation. The resulting linear difference equation takes the form

$$x((k+1)T) = \mathbf{A}\, x(kT) + \mathbf{B}\, u(kT) \qquad (A6)$$

where **A** and **B** are matrices. Digital control methods can be used to study Eq. (A6)

POSITIONAL CONTROL

The goal of robot control is to move the end-effector according to the requirements of the task being performed by the robotic manipulator. The simplest requirement is to move the end-effector from its initial position to a certain desired position without imposing any constraint on the path that the end-effector traces during its motion. When path constraints and/or other constraints are imposed, the problem becomes involved. A massive amount of literature is devoted to the solution of the constrained path problem. Trajectory planning, minimum-time path tracking, minimum-energy path planning, collision-free path planning, collision-avoidance path planning are but examples of such cases. A good introduction and survey of this problem is presented in (2).

Consider an n-joint manipulator and let y(t) be a vector representing the position and orientation, in Cartesian coordinates, of the end-effector. Also, let $x_J(t)$ be the position of the jth joint in joint coordinates. Then,

$$y(t) = f(x_1(t), x_2(t),....,x_n(t)) \qquad A(7)$$

for some vector-valued function f. In general, f is highly nonlinear. A path given in terms of the position of the end-effector can be converted into a trajectory traced by the joints by inverting the function f. For example, to move the end-effector from position y_0 at time t_o to position y_1 at time t_1, we need to move the jth joint from position $x_J(t_o)$ to $x_J(t_1)$,

where

$$y_0 = f(x_1(t_0), ...,x_J(t_0),....,x_n(t_0))$$

and

$$y_1 = f(x_1(t_1), ...,x_J(t_1),....,x_n(t_1))$$

or using the inverse $f^{(-1)}$, we can write

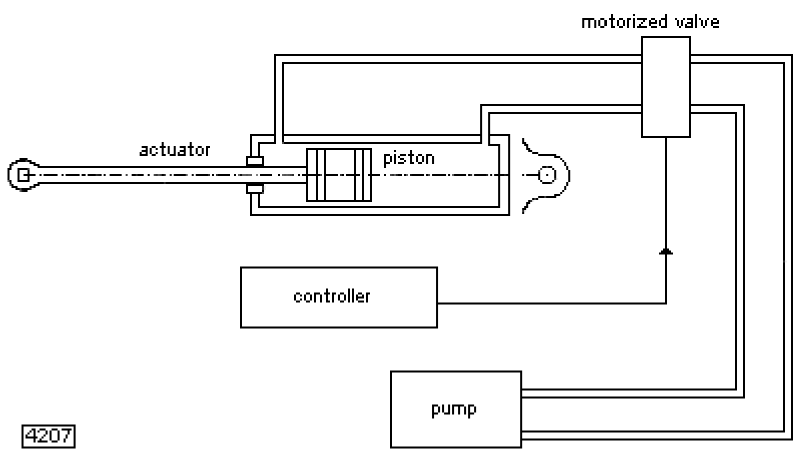
$$(x_1(t_0),...,x_n(t_0)) = f^{(-1)}(y_0)$$

and

$$(x_1(t_1),...,x_n(t_1)) = f^{(-1)}(y_1)$$

In general, the inverse $f^{(-1)}$ is not unique. However, any such value will do unless further restrictions are imposed.

Figure 2: A hydraulic actuator.



In many cases, the end-effector is required to move from an initial position to a final position along a prescribed path. In this case, it is not enough to know the initial and final position of the joints. Rather, intermediate points are also important. One way to track the end-effector along the prescribed path is to approximate the path by piece-wise linear segments and to move the end-effector between the end-points of these segments. Using spline functions interpolation instead of linear pieces results in a smoother motion.

Constraints on other variables like joint speeds, accelerations and torques can be imposed. Also, time and energy constraints are popular. If the works space contains other moving or stationary objects, then only collision-free paths are allowed and collision-avoidance is needed.

The constrained-path tracking problems are difficult to solve in general. Many simplifying assumptions were used in the literature in order to make the problem tractable. In particular, either the Coriolis and centrifugal terms in the dynamic equations are ignored, or some of the constraints are ignored or both (2).

SELECTED LITERATURE SURVEY

There exists massive amounts of publications on robotic control, and it is not possible to survey all relevant literature within the scope of this work. Therefore, we here present a selected list of literature on the topics of interest.

Point-to-point control of robotic manipulators was studied by Paul et al (3). Whitney (4) suggested a method for smooth point-to-point control of robotic manipulators by imposing speed constraints at the transient points along the path. The application of adaptive control methods to robotic control was extensively investigated (5-9). Artificial intelligence methods were also applied for the learning control of robots, particularly for mobile autonomous robots (10-14). Constrained-path tracking poses the most interesting of problems.

Time-optimal and energy-optimal path planning were studied by several authors (15-20). Collision-free path planning was investigated just as widely (21-26). Much effort went into devising efficient computational methods as well as designing hardware architectures (27-40) due to their relevance for the real-time control of robots.

A very interesting recent trend in robotic research is the application of artificial neural network algorithms for the study of the inverse kinetic equations, path tracking and control. The highly nonlinear nature of the dynamic equations of robotic manipulators make it plausible that neural network algorithms be used (41-49). Another interesting trend is the application of fuzzy logic to the learning control of robots (50).

CONCLUDING REMARKS

It is clear that the dividing line between an ordinary machine and the robot goes through the controller. It is perhaps not surprising that the single most costly item in a robotic system is the controller itself. It is therefore anticipated that significant developments in the area of robotic controls will be heralded in the years ahead, parallel with the developments on computers.

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