Updating the control systems of a Trallfa industrial robot

A. Ray,* The Charles Stark Draper Laboratory Inc., USA

A scheme for conversion from magnetic tape to computer control of an industrial robot has been developed. Programming has been extended from the normal teach capability to operation from a remote hand-held joystick as well as from the computer console.

WITH THE advent of inexpensive microprocessors and associated computer technology, a number of manufacturers in the USA, Europe and Japan are building computer-controlled robots.[1] The earlier versions of industrial robots were equipped with magnetic tape memory systems that had limited *teach* and *repeat* capabilities due to lack of flexibility to adapt for process dynamics.

In many production-oriented industries such as steel and aluminium mills, the existing robots with magnetic tape memory are obsolete and may have to be replaced by modern computer-controlled robots. If the conversion from magnetic tape to computer system is practical and economical for these robots, then the operations will be more flexible, and advanced control algorithms could be implemented in the software. These modified robots are likely to satisfy many requirements of complex production processes, and expensive replacements of the existing robots may be avoided.

To overcome the limited access and storage capabilities of magnetic tapes and to improve dynamic performance of robot arms, a scheme for conversion to computer control has been developed, demonstrated and evaluated. As a proof-of-concept, the magnetic tape system of a Trallfa 3000 robot has been replaced by a PDP 11/40 minicomputer which allows faster responses and additional movements of the robot arm.

In addition to the lead-through teach capability, the modified robot can be operated by a remotely located hand-held joystick as well as from the computer console. In the future, this
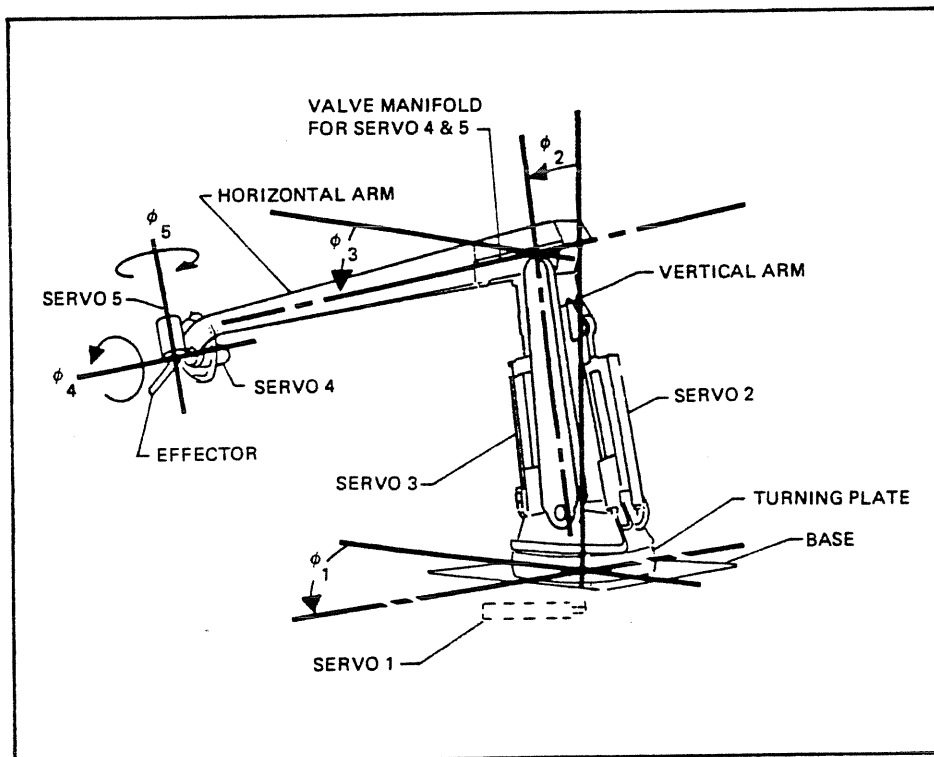

Fig. 1. Schematic diagram for robot arm movements.

control scheme may be implemented by microprocessors and/or a time-shared minicomputer instead of a dedicated minicomputer.

The Trallfa 3000 robot is an electronically controlled machine made specifically for industrial painting. The robot is designed to emulate human body movements.

To complete a specified task, a human operator guides the robot through the necessary movements so that identical tasks can be subsequently performed by the robot. This operation is called lead-through *teach* mode; the sequence of movements is recorded on a magnetic tape with a maximum cycle time of 180 seconds. In the *repeat* mode, the robot reproduces the sequence memorised in the magnetic tape.

The machine under study is a five-axis robot as shown schematically in Fig. 1. The movements of the axes are as follows:

- axis 1 – rotary motion ϕ_1 of the base;
- axis 2 – forward and backward motion ϕ_2 of the vertical arm;
- axis 3 – up and down movement ϕ_3 of the horizontal arm;
- axis 4 – vertical rotary movement ϕ_4 of the effector;
- axis 5 – horizontal rotary movement ϕ_5 of the effector.

In its original form, the Trallfa robot consists of three basic components:

- robot arm and manipulator, with each axis having a hydraulic drive cylinder and a servo-valve;
- hydraulic power pack;
- electronic console incorporating a

number of tape cassette holders, and recording and playback control.[2]

Tape problems

The magnetic tape cassette has the following problems that hinder fast ⅃ reliable operation:[2]

□ the tape may be folded inside the cartridge in random loops resulting in fouling and breakage;

□ the search time delay may be as high as 30 seconds, which may not be acceptable for fast production processes;

□ maximum cycle time of 180 seconds may not be sufficient for many complex production processes.

These problems can be eliminated by a computer that offers random access memory and practically unlimited program length. The major advantages of a computer control system are:

□ flexibility of software structure which allows introduction of advanced control and system identification schemes such as adaptive control and pattern recognition;[3]

□ more reliable control scheme and large data storage capability which are less prone to drift and noise than hardware;

vastly increased program lengths in the *teach/repeat* modes, having program access time less than one second.

The other major problem associated with the Trallfa robot is its inability to accept remote commands during *teach* mode. This problem was solved by the introduction of a hand-held joystick through which an operator can *teach* the robot and exchange information with the computer.

The joystick has five axes, each of which is equipped with spring return potentiometers having negligible dead band. If the joystick is shifted from the neutral position, the steady-state response of the robot arm is identically equal to the angular displacement of the joystick.

The advantages of remote control by a joystick in comparison to the local lead-through operation in the *teach* mode are:

□ added capability to function in hazardous environment;

□ increased speed of the robot arm, especially when moving with high loads;

□ reduction in switching time from *teach* to *repeat* mode, since fastening and unfastening of teaching handles are not required;

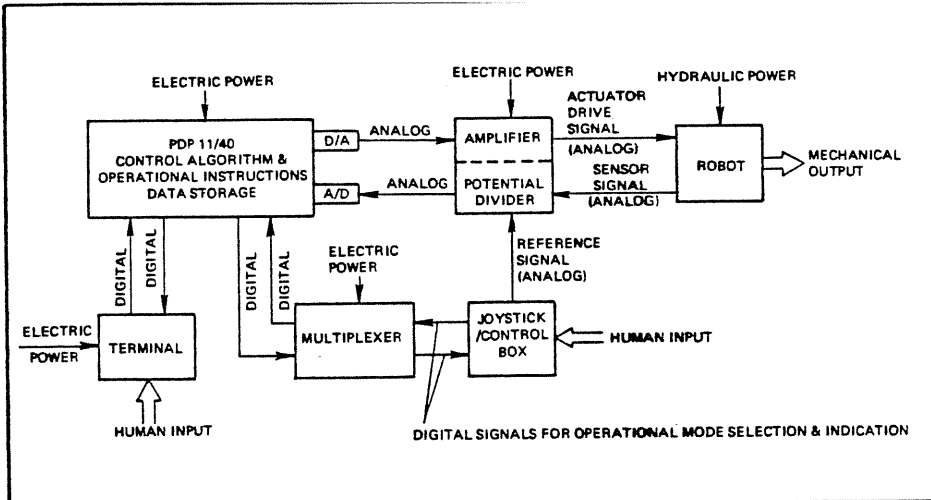□ improved position control due to better sensitivity of the joystick

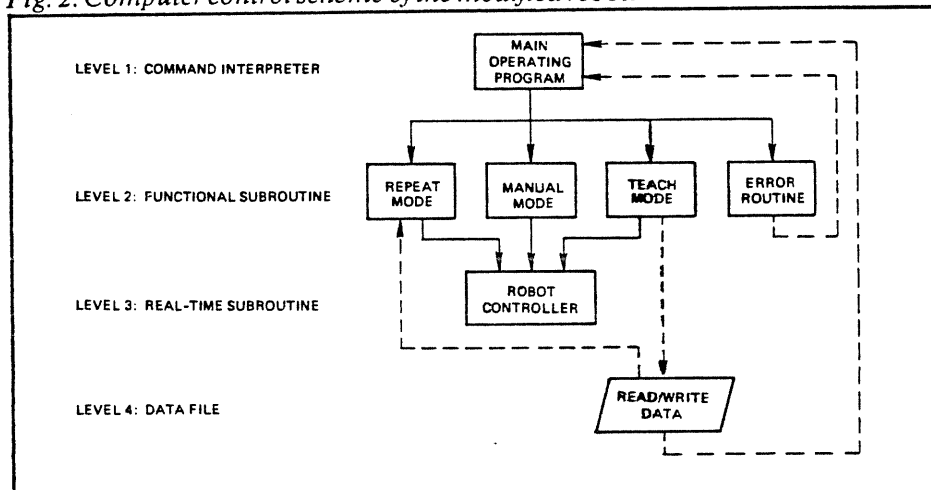Fig. 2. Computer control scheme of the modified robot.

Fig. 3. Hierarchy of software structure.

handle.

Computer control

As a first step towards implementing a computer control system, a PDP 11/40 minicomputer, a 14-channel multiplexer and a special purpose digital multimeter were chosen to demonstrate feasibility of the concept. Since the use of a minicomputer as a dedicated computer for one robot may not be economically justifiable, the control system should be partly or completely implemented by inexpensive microprocessors in the future.

The computer control scheme is shown in Fig. 2. The joystick/control box provides a control centre and its operation is reasonably simple. The joystick provides reference signals for independent motion of the five robot axes. The control box interfaces with the computer through a multiplexer for operational mode selection and indication. There are six switches for selecting operation modes and five lights indicate the operating status of the robot.
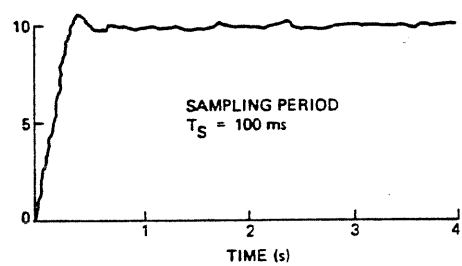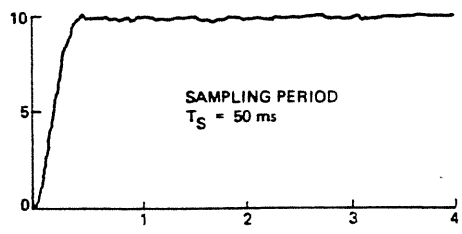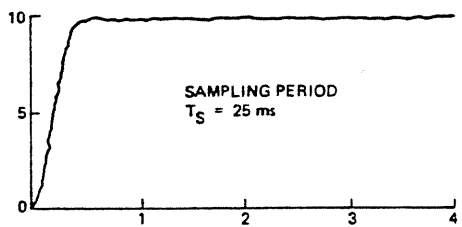
The operational modes are determined through selection of the four positions of the control switch, *manual, teach, repeat* and *pause,* and pressing the *start* or *stop* buttons, all of

which are installed on the control/joystick box. The five signal lights, *stand-by, ready, end, wait,* and *error,* that indicate the operational modes are located close to the control switch. The operational modes are described below.

Teach: in this mode, the operator guides the robot through a desired sequence either by joystick movement or in a lead-through action. If the joystick is used, the displacement of the joystick from the neutral position determines the angular velocity of the robot arm in the respective direction. The *teach* mode is entered by setting the control switch to *teach* position. When the *stand-by* light is turned on, the *start* button is pressed. At this point, the computer opens a new file and transmits a signal to turn off the *stand-by* light and to turn on the *ready* light. The *teach* sequence is terminated when the *stop* button is pushed – the computer closes the data file, and both *ready* and *end* lights are turned on.

Repeat: to enter this mode, the operator puts the control switch to *repeat,* and as the *stand-by* light is on, the *start* button is pressed. The computer searches for the appropriate data file to repeat the sequence, and as soon

Fig. 4. Transient response of robot arm with low controller gain at extended position.

modes; the *teach* sequence is terminated by the *stop* button and stored under a newly created file name.

The REPEAT subroutine loads the file to be repeated unless there is any error message. At the end of the file or if the operator terminates the sequence by the *stop* button, control is returned to the main program.

The subroutine CONTROL provides appropriate control strategies in discrete time domain with zero-order-hold for all operational modes.[5] Proportional control logic is used, i.e., the controller output is proportional to the positional error which is equal to the difference between desired position and actual position of the arm.[3]

The following control strategies are used (please see nomenclature for symbol definition):

□ *Repeat* mode. For each axis, the manipulated variable at the nth sample is given by

$$U(n) = K_p[X_t(n) - X_f(n)] \qquad (1)$$

□ *Teach* and *Manual* modes. In these modes, the operator normally uses the joystick to move the robot arm. Therefore, the control algorithm with respect to joystick movement will be derived.

The manipulated variables U at the nth and (n − 1)th samples are given in terms of corresponding reference signals.

$$U(n) = K_p[X_r(n) - X_f(n)] \qquad (2)$$

$$U(n-1) = K_p[X_r(n-1) - X_f(n-1)] (3)$$

However, the reference signal $X_r(n)$ at the nth sample can be obtained in terms of the parameters at the (n − 1)th sample.

$$X_r(n) = X_r(n-1) + ST_s\theta(n-1) \quad (4)$$

Rearranging equations (2), (3) and (4) results

$$U(n) = U(n-1) + K_p[ST_s\theta(n-1) - (X_f(n) - X_f(n-1)] \qquad (5)$$

Within respect to a given initial position, it is justifiable to set $U(0) = 0$ when $\theta(0) = 0$. Then, the recursive relation (5) yields the manipulated variable $U(n)$ for all samples n > 0.

In all modes of operation, the angular velocity of the robot arm varies in direct relationship with the respective manipulated variable U. Therefore, to avoid drift of the robot arm and to introduce greater sensitivity for large deviation from the desired position, the manipulated

as the file is opened, the *ready* light is turned on. At the end of the sequence, the file is closed, and both *ready* and *end* lights are on. Before completion of the sequence, the operator may abort the *repeat* mode by pressing the *stop* button.

Manual: this mode is similar to the *teach* mode with the exception that no sequence of data is stored in any computer file. To enter this mode, the control switch is set to *manual* position, and when the *stand-by* light is turned on, the *start* button is pushed. As the *ready* light is turned on, the operator may move the robot arm by the joystick or in a lead-through fashion. This mode can be terminated by pushing the *stop* button. Both *ready* and *end* lights are turned on at the termination of *manual* mode.

Pause: to pause any mode of operation, the control switch may be put to the *pause* position when the *ready* light is turned off and the *wait* light is turned on. At this stage, the operator can either terminate the mode by pressing the *stop* button or resume by putting the control switch to the original position and then pressing the *start* button.

During any mode, if the computer detects an error, the operator is alerted

by turning on the *error* light. The light is turned off when the operator clears the error and presses the *start* button. A typical error is to ask the computer to access a non-existent data file in the *repeat* mode.

Software

The software for robot control is written in FORTRAN language for use with the RT-11 operating system of Digital Equipment Corporation.[4] The software package consists of a set of programs with four levels of hierarchy as shown in Fig. 3.

The main operating program controls the overall execution of the system and interprets commands from the control switch and the keyboard. On interpretation of commands, the main program may call one or more subroutines. For example, if an error is detected in the input command, the subroutine ERROR is called, which keeps the warning ERROR light flashing until the operator takes a corrective action.

The TEACH and REPEAT subroutines are structurally similar. At the start of the *teach* mode, the initial position of the robot arm is ensured so that the arm starts from an identical position in the subsequent *repeat*

K_p	controller gain
M	modified manipulated variable (input to servo-valve)
n	sampling instant
S	sensitivity constant for joystick potentiometers
s	Laplace transform variable
T_s	sampling period
U	manipulated variable (controller output)
X_f	feedback signal from robot arm position transducers
X_r	reference signal for robot arm position
X_t	desired robot arm position (determined in *teach* mode)
δ	offset for servo-valve command signal ($\delta \geq 0$)
ϕ	angular position of robot arm
θ	angular displacement of joystick handle from neutral position

variables derived in equations (1) and (5) are modified as

$$M(n) = \begin{cases} 0 \text{ for } |U(n)| < \delta \\ [|U(n)| - \delta]^2 \text{ sgn } (U(n)) \text{ for } \\ |U(n)| \geq \delta \end{cases}$$

where

$$\text{sgn } (U(n)) = \begin{cases} 1 \text{ for } U(n) \geq 0 \\ -1 \text{ for } U(n) < 0 \end{cases}$$

In the interactive mode, the program can be interrupted from the keyboard to alter the control parameters such as sampling interval and controller gain. The operator may use the keyboard to move the robot arm to any desired position.

System performance

The robot control scheme is closed loop and works in discrete time. Therefore, the system performance depends on both sampling period T_s and controller gain K_p. To evaluate the dynamic response of the robot arm, step disturbances were applied from initial neutral positions of individual joystick axes.

As a typical example, test results for a 10° step increase (8.3% of maximum travel range 120°) in the joystick angle θ_1 for rotary base motion from its neutral position (with extended arm) are demonstrated in Fig. 4 and 5 for different settings of the control parameters T_s and K_p. Fig. 4 shows the effects of varying the sampling period at a constant value of $K_p = 2.5$. For a sampling period of 25 milliseconds, the system performance approaches that of a continuous-time system. As the sampling period T_s is increased to 50 milliseconds, tiny ripples are generated; increasing T_s further to 100 milliseconds, the system shows a slight overshoot but the oscillations decay rapidly.

Fig. 5 shows these effects for a higher value of $K_p = 7.5$. The system performance is oscillatory even for a small value of T_s. As T_s is increased, the system performance deteriorates to the extent of sustained oscillations.

The robot has a varying spatial geometry and is therefore expected to exhibit different system dynamics for various arm configurations. When the arm is retracted, the moment of inertia about the axis is the smallest. This configuration yields a wider bandwidth than that with arms extended.

The open loop transfer functions of the robot arm angular position for rotary base motion versus the corresponding controller output were obtained for the retracted and extended arm positions. Sinusoidal in-
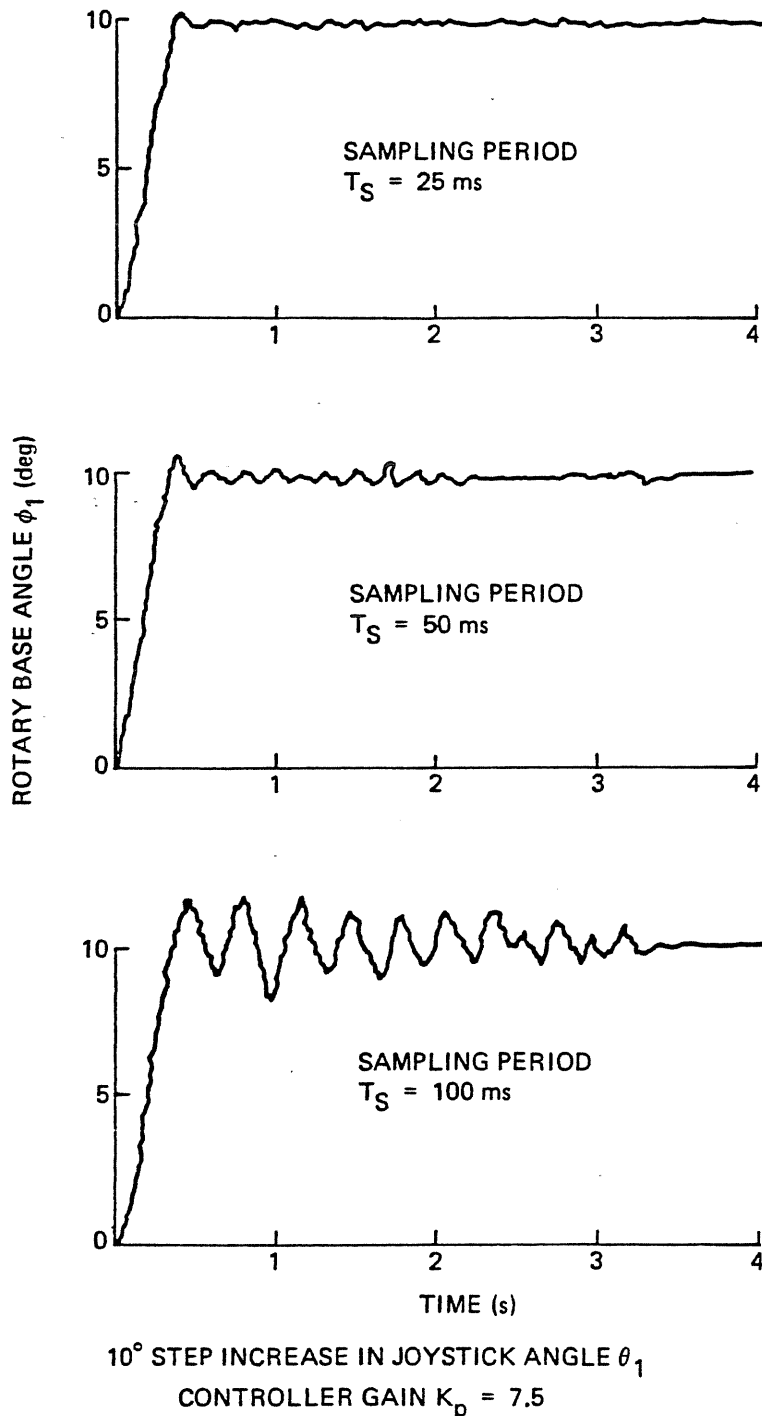

Fig. 5. Transient response of robot arm with high controller gain at extended position.

Fig. 6. *Frequency response of robot arm at retracted position.*

Fig. 7. *Frequency response of robot arm at extended position.*

free integrator and a dominant finite pole. Assuming a linear model and a simple second order approximation, the open loop transfer functions are

$$\frac{\theta_1}{U}(s) = \frac{4.1}{s(0.031s+1)} \text{ for arm retracted}$$

(7)

$$\frac{\theta_1}{U}(s) = \frac{3.9}{s(0.10s+1)} \text{ for arm extended}$$

(8)

The transfer functions include electronic power amplifier, servovalve, actuators and machine structure. The time constant varies significantly with arm position which exhibits the non-linear, dynamic characteristics of the robot.

Conversion from magnetic tape cassette to computer control has been demonstrated and evaluated for Trallfa 3000 robot. The modified robot is conveniently operated by a remotely located hand-held joystick, and the control parameters in the software algorithm can be updated from the computer console to adapt for the changing process dynamics. These computer-controlled robots are likely to satisfy many requirements of complex production processes in modern industries, and thus expensive replacements of the existing (tape cassette type) robots may be avoided.

In the future, this control scheme may be partly or completely implemented by inexpensive microprocessors. If several robots or automated machines are in operation in a production shop, a hierarchial control strategy could be developed so that individual machines may be controlled by their own dedicated microcomputers for lower level functions such as servo-valve control and data collection, and one or more minicomputers may operate in the supervisory role to all machines for more complex functions such as co-ordinate transformation.

References

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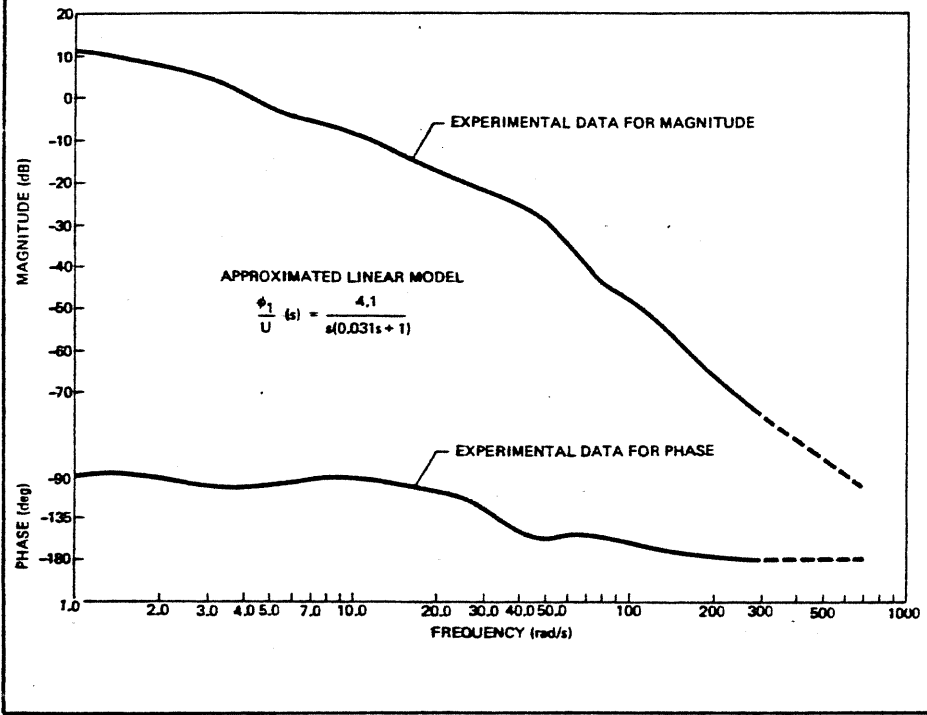5. Kuo, B. C., Digital Control Systems, SRL Publishing Co., Champaign, Illinois, USA, 1977.
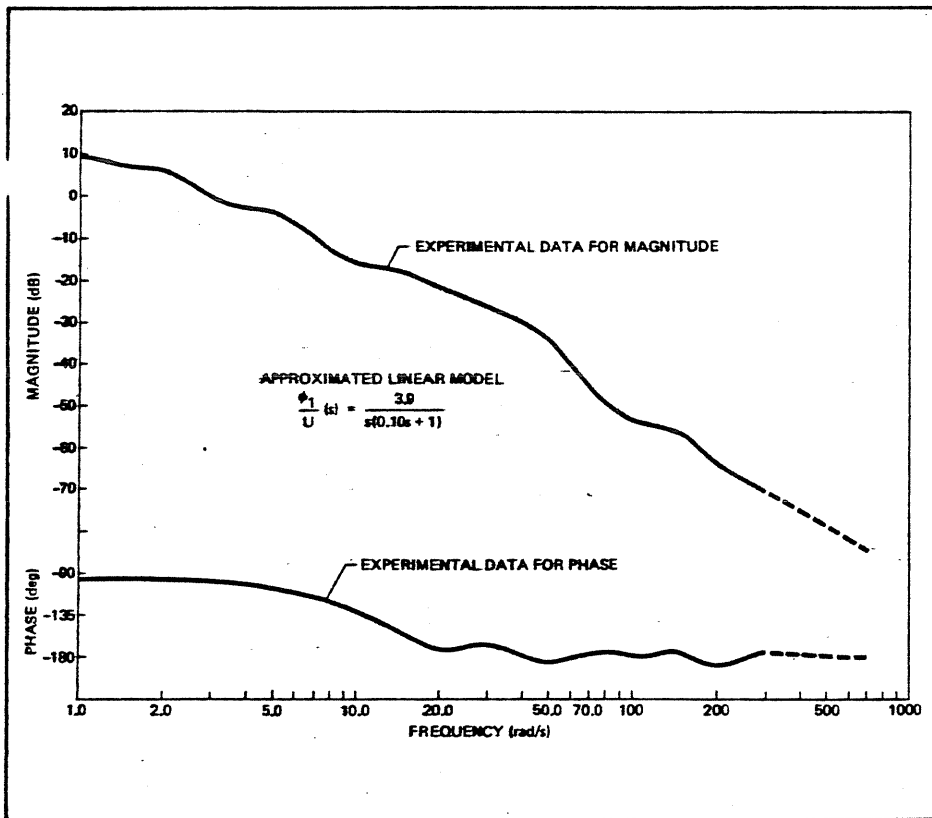
puts equivalent to an amplitude of ± 5° angular displacement of rotary base angle at frequences ranging from to 300 radians/second were fed to the controller with feedback loop open, i.e., θ_f was set to 0. The controller gain K_p was set to 1 so that the loop gain becomes equal to the process gain, and the sampling period T_s was set to 25 milliseconds.

Frequency response

Transient data were first collected on a disk, and then analysed to yield frequency response. Bode plots of the rotary base angular position θ_1, versus controller output U are given in Figs. 6 and 7 for retracted and extended arm positions, respectively.

These plots show the existence of a