Trajectory Control of a Multi-axes Robot with Electrical Servo Drives

Werner Leonhard

The control of multi-axis robots serves as an example of complex mechanical control plants combining the need for high accuracy with speed of response. The requirements and how they can be met are shown with a combination of microelectronic components in the form of a modular microcomputer system.

Introduction

The purpose of a mechanical manipulator or robot is to position the tool or workpiece at a prescribed point or to move it along a trajectory in order to relieve workmen of heavy, dangerous, or tedious mechanical labor. There are many different robot designs consisting of multi-jointed links; in order to allow general unimpeded motion within a given workspace, six independently driven axes are needed. For instance, three main axes for positioning the robot hand and three hand axes for pointing it in a certain direction are needed; in addition, there are the auxiliary motions of the tool.

For activating the various axes, different drive principles - electric, hydraulic or pneumatic - are being employed. Except for special cases, electrical servo drives have evolved as the preferred solution in recent years, because of their superior controllability; the usual power ratings cover the range up to about 10 kW. In order to achieve high mobility of the robot with limited drive power, lightweight construction is important; on the other hand, mechanical stiffness is mandatory for the robot hand to follow a prescribed trajectory. The reason is that the hand position cannot normally be measured directly but must be derived from the rotation of drive shafts, so that bending or mechanical oscillations would result in a loss of accuracy. An important condition for a servo drive is low inertia and the ability to supply high short term peak torque for overcoming frictional load and for rapidly accelerating or stopping the motion of the arm.

These requirements can be met with dc disk motors having permanent magnet excitation and an iron-less armature, supplied by a pulse-width modulated transistor chopper; however, the mechanical commutator causes limitations in standstill and at high speed, in addition to restrictions in explosive or corrosive atmosphere.

On the other hand, adjustable speed ac drives, possessing no moving contacts, have in the past been hampered by the lack of economical power converters and by the fact that the complex nonlinear dynamics of ac motors have made it difficult to design high performance controls for use as servo drives. These difficulties have been overcome in recent years thanks to progress in the semiconductor field, i.e., by the advances of microelectronics and microelectronics. AC servo drives are now fully competitive in performance, they possess a higher impulse torque and higher speed capability than their dc predecessors [8]. There is a choice of two designs:

- synchronous motors with high energy rare-earth permanent magnets on the rotor (including the so-called brushless dc motors), and
- induction motors with cage rotor.

The synchronous motor is easier to control and exhibits higher efficiency; it is preferred for positioning and feed drives, whereas the inherently lower cost induction motor, permitting field weakening and a correspondingly wide speed range, is ideally suited for spindle drives on machine tools. In contrast to dc drives, the signal processing for ac drive control is of considerable complexity that can effectively be handled only by microelectronics.

Permanently excited synchronous motors are available in the usual slim (for low inertia) drum shape with radial field or as short disk motors with axial field; both are used for robot drives, there is no difference in control.

A robot is a multivariable plant, where mechanical power is applied at the drive shafts, resulting in changing position and orientation of the tool. The kinematic and dynamic interactions are highly nonlinear, making it very unlikely that general top-down methods for designing robot controls can be found. It is therefore common practice, also applied here, to start at the individual servo drive, and to try to separate the dynamics of the different motions by compensating the interaction torques with the help of load models, while decoupling the kinematic interactions by coordinate transformation [1,5,14].

![Fig. 1. Model of drive train with split inertia and resilient gear.](image-url)
However, this still creates formidable problems of on-line signal processing, calling for a powerful control computer. This paper addresses the problems of robot control and presents a review of the experimental work in our lab during the past years, showing how these problems can be solved with a modular multimicrocomputer system that offers the necessary flexibility at acceptable cost.

**Robot Control with Geared Servo-Drives**

All present day electrical machines are characterized by the fact that the tangential forces per unit surface of the rotor are limited by iron saturation and current density in the conductors; hence the power to weight ratio can only be raised by high speed operation. Since most robot drive axes call instead for high torque and low speed, for example 4000 nM at 15 min⁻¹ for the vertical axis of a medium size welding robot, a direct drive is normally not practical; instead, the motors are connected to the load through reduction gears which can accommodate large single stage reduction ratios, however at the cost of noticeable resilience between the high speed and low speed drive shafts. This must be taken into account when controlling the robot. Fig. 1 shows a block diagram of a single axis servo drive, possibly one axis of a robot, where the drive train is divided into two lumped inertias, that of the motor and the load, separated by the resilience of a gear which may even exhibit backlash. \( J_m \), \( J_L \), are the respective inertias, \( n \) is the gear ratio; \( \omega_m, \omega_L \) are the angular positions, \( \omega_m, \omega_L \) the angular velocities.

Motion is initiated through the internal driving torque \( m_m \) of the motor which is usually governed by a fast torque control loop with the torque command \( m_{cmd} \); torque control is important on position controlled servo drives that may have to operate for extended periods at very low speeds or in standstill and where current limit is mandatory. The effective delay of the torque loop is a measure for the dynamic performance of the drive, 0.5-1.0 ms are achievable with today's components, for example signal processors.

Each of the servo drives of a multi-axis robot may be represented by a scheme like the one shown in Fig. 1. The interactions between the different axes take place through the dynamic load torques \( m_t \) that contain gravitational, centrifugal and Coriolis terms depending on speeds and angular positions of all other drives; the dynamic effects of the hand axes on the other drives can often be neglected.

Another effect is the dependence of the load inertia \( J_t \) on the geometrical operating point of the robot, i.e., on all the angles of rotation. As a consequence, the parameters of the speed controllers should be updated in order to obtain uniform response as the robot moves in its workspace. Of course, this is less important with robot designs having very large gear reduction ratios because then the total inertia is dominated by the motors.

For reasons of simplicity and cost, the speed and position sensors are often connected to the motor shaft or an intermediate shaft at the input side of the gear, so that the gear and the mechanical linkage of the arm are outside the closed position control loop resulting in unobserved position errors of the robot hand. Bending of the robots links is usually negligible, compared with the errors caused by elasticity of the gears.

**Cascade Control**

A plant motion of the robot hand can only be expected when each joint axis is guided on a smooth path, with the first and second derivatives of all rotational reference positions being continuous; otherwise there would be abrupt changes of the driving torques which could cause mechanical oscillations and excite resonances. The reference path must be generated prior to the production run in order to assure a time-optimal trajectory with maximum mean velocity.

Small dynamic deviations between reference and actual trajectory are obtained by a well-known cascaded multiloop feedback structure shown in Fig. 2 for torque (or acceleration), speed and position in combination with a dynamic model generating a set of reference signals for each axis (e.g. [7]). By adding these signals in feed-forward mode at the inputs of the appropriate controllers, the dynamic position error is greatly reduced, because none of the controllers is saturated, not even temporarily. The main action is initiated by the feed-forward signals while the outer control loops for speed and position of each axis are serving a supervisory and corrective purpose. This principle of "structured state control" has been proven in many different applications. In contrast to general state space control methods, the design is straightforward and fully transparent, where each controller is performing a unique and clearly defined task and where the loops can be closed one after the other during commissioning; also, it is easy to limit internal variables, such as torque and velocity. Depending on the choice of NF in the reference model, the position control could be linear or time optimal for point-to-point transitions.

The speed feedback signal is derived through a digital filter from the high resolution signal for angular position, i.e., without an extra speed sensor.

The parameters of the reference models are computed off-line and coordinated with the other axes of motion in order to obtain the desired spatial trajectory. With a robot, the reference model could consist of a set of continuous spline functions connecting given fix points. Since the task of trajectory planning and reference path generation is normally carried out in Cartesian coordinates, a numerical transformation of the reference quantities from Cartesian to joint coordinates is needed. Further improvements of the quality in tracking the given reference path are achieved by:

- continually updating the parameters of the speed controllers in view of the known geometry-dependent inertias of the drive axes, and
- by estimating the dynamic load torque \( m_t \) exerted on each axis and compensating it by feed-forward injection at the appropriate reference input ("inverse load model") [3].

Execution of the complex calculations in the short sampling intervals of a high performance robot control scheme (1-2 ms) is not a trivial task for a microcomputer.
ing its limitations. Some results will be given later.

Reference Trajectory

The purpose of robot control is to accurately guide the hand on a spatial reference trajectory $x_{Re}(t)$ by commanding its position and orientation in Cartesian coordinates; the derivatives $x_{Re}'(t)$ and $x_{Re}''(t)$ are also prescribed in order to assure continuity and reduce mechanical resonances. However, as the Cartesian position of the robot hand is normally not accessible by measurement, control of a joint trajectory $x_{Ja}(t)$ must be substituted instead, leading to a further formidable task of on-line signal processing: converting the prescribed Cartesian trajectory $x_{Re}(t)$ to an equivalent trajectory $x_{Ja}(t)$ on joint level.

Inverse coordinate transformation with a six-axis robot is a demanding numerical problem that requires high accuracy and in general cannot be solved in closed form; with some robot designs the solution is not even unique. Also, there may be singular points, when some of the axes fall in line, requiring special consideration.

Sensory Feedback

Best precision in trajectory control can of course be expected when the position of the robot hand is guided not by indirect measurements at some remote drive shafts but by direct accurate measurement in Cartesian coordinates. This could be achieved with hand-
desired position, where guidance by sensory feedback can take over; hence, trajectory control on joint level is still needed for moving the hand outside the capture range. This is described in Fig. 4 showing the complete robot control system in general terms [14]. It contains the decoupled multiloop control scheme discussed before, the kinematic (out-bound) transformation performed by the mechanical linkage, which is duplicated in the control section for supervisory purposes, as well as the inbound inverse transformation based on the Cartesian reference trajectory. In addition there is the hand held sensor tracking a stationary target, i.e., the welding seam.

Clearly, in order to perform suitable corrective action through the robot control, any signals indicating sensor based position errors must first be transformed into Cartesian coordinates to be superimposed on the original reference trajectory. The magnitude of these correcting signals should be limited in order not to cause undefined deviations from the preprogrammed reference path; the reference trajectory must remain available as a second line of defence, otherwise the motion would have to be stopped for safety reasons, if the sensor signal is corrupted by noise or becomes temporarily invalid. In an advanced version of robot control, the corrective signals produced by the sensor can be used to modify the programmed reference trajectory, thus creating a self-learning effect.

**Experimental Results with AC Servo Drives**

It was shown [9] that the complete digital torque, speed and position control of an ac motor can be performed by a signal processor TMS 32010 in 250 µs intervals, resulting in 4 kHz switching frequency of the inverter and synchronous sampling of the control signals; for small signal amplitude this leads to an effective lag of the torque control loop of 0.5-1.0 ms which is sufficient for rejection of disturbance forces and for damping resonances in the mechanical robot structure. Fig. 5 depicts positional transients of a 1.2 kW ac servo drive, built in our lab. With new types of transistors the switching frequency of the inverter can be increased beyond 20 kHz, i.e., out of audible range, but not much would be gained by equally raising the sampling frequency of the controllers.

AC servo drives have been installed and tested in our lab on an experimental rig with two parallel axes; one of the motors was a permanent magnet synchronous motor, as described, the other an induction motor with cage rotor. The control of an induction motor is complicated by the fact that the position and magnitude of the flux wave, generated by stator and rotor currents, must be computed on-line using a model [7, 9, 17].

**Experimental Results with the Control of a Six-Axis Robot**

Much of the general work on robot control during the past years involved an industrial six-jointed robot VW-G60 having a workspace of about 2 m radius and a payload of 60 kg. This equipment, being of somewhat earlier design, is powered by dc-disk motors, supplied from quadrant transistor choppers with 5 kHz switching frequency. The effective lag of the armature current control loops is below 1 ms; since armature current of a permanently excited dc-motor is proportional to torque, this corresponds to the block "torque control loop" in Fig. 1. The angular positions of the six axes are measured by 16 bit optical encoders, attached to the high speed sides of the gears. The measured data are transmitted by optical links to the control computer which has been designed and built in the lab [16]. From the outset it was planned to provide adequate processing power in order to reduce the sampling period in the trajectory control mode to below 2 ms, necessary for exploiting the inherent potential of the mechanical and electrical equipment.

The solution chosen was a modular microcomputer system as shown in Fig. 6, where an expandable number of units, operating in parallel, is linked to a common bus.
Each board contains a 16-bit microcomputer and a dedicated signal processor; the assignment of tasks has been changing over the years, as bottlenecks developed and the emphasis of the work shifted. The drawback of the signal processor based modular computer is, of course, that it must be programmed in Assembler. More recently, the control computer was extended at the front end by a personal computer (AT) for off-line trajectory planning and optimisation and at the rear by a high-speed vector processor card for performing the interpolation of reference signals and the coordinate transformations which require a great deal of processing power [4, 13-16]. The characteristics of the control system and the effects of some of the options mentioned earlier will now be discussed using examples of actual measurements.

The traces in Fig. 7 demonstrate the effect of speed and acceleration feedforward on the dynamic position error of one of the controlled axes [16]. The transient represents a time-optimal step response of the position control loop at reduced speed. It is seen that this method of improving the tracking performance is highly effective; when the feedforward signals are properly tuned, the dynamic position error can be reduced by an order of magnitude.

Using Fig. 3 it was discussed that the dynamic position error caused by elasticity of the gears may be reduced by mounting a second sensor directly on the output shaft, thus measuring the angular position of the robot link. This seemed a worthwhile experiment on the three main axes of the available robot, particularly joint 2 which is heavily loaded by gravitational unbalance torque (unless a pneumatic support cylinder is activated) [14]. The result is seen in Fig. 8 where a positioning transient at reduced maximum speed is plotted. The dynamic angular position error, measured at the output shaft of the gear, is drawn for both modes of control, when the position feedback is taken from:

- the normal encoder, connected to the input shaft, and
- from an additional incremental sensor with high resolution channel, attached to the output shaft of the gear (Fig. 3).

There is a considerable improvement, of course at the cost of additional hardware and increased complexity of the control.

A fast torque control loop is clearly the base on which any advanced robot control scheme must be built; in case of a dc-motor it may have the simple form of an analogue current control loop, whereas a more elaborate digital control with a signal processor or a special LSI chip is needed for a high performance ac servo drive.

At the next higher levels, speed and position of each motor are to be controlled. While the position control loop should definitely be digital in view of the required accuracy, as well as for storing and processing of reference data, analogue techniques are still arguable for the speed control loop; in fact many of today's dc-driven robots employ analogue speed control with tachometers on the motor shaft. However, when improved performance, for instance by compensating the varying load inertia is desired, Fig. 3, digital speed control is preferable; this does not require a special speed sensor because the information can be extracted from the joint position, either by computing simple differences or with a more sophisticated digital filter. All dc-tachogenerators attached to the dc motors of the VW-G 60 robot had in fact been disconnected for the tests shown.

An important feature of the multiloop control structure in Fig. 2 is that all the controllers are of a simple PI-type, comprising P and I controllers as special cases. With the necessary limit checks, a PI-controller function with fixed parameters, implemented on a TMS 32010 signal processor in integer arithmetic, requires about 8 μs, so that 12 controllers and 6 digital filters can be computed in less than 200 μs by one of the microcomputer boards shown in Fig. 6.

**Coordinate Transformation and Inverse Load Model**

More time is needed for computing the inverse load model, Fig. 4, in order to dynamically decouple the individual axes; in case of the VW-G 60 robot, it was sufficient to test this option on the three main axes because the hand axes cause little dynamic interactions. Again with integer arithmetic, one signal processor could handle this complicated task in about 800 μs, so that the aim of achieving a sampling period of 1.25 ms for all the control functions could be reached.

The quality of the feed-forward signals derived from the inverse model may be judged by the trace in Fig. 9 measured at one of the three main axes [14]. They show the predicted load torque supplied from the inverse model, together with the total torque reference, where the corrective signal from the speed controller has been added. The measurements were
taken at close to maximum load of the drive motors. The inverse model included also friction terms.

The result of this corrective measure is seen in Fig. 10 for the same trajectory. It shows the dynamic position error of axis 2 without torque feed-forward, with feed-forward of accelerating torque only and with the full three-axes inverse model. The improvements are substantial.

Even when restricting the inverse load model to the main axes, the dynamic interactions are quite involved. A complete inverse load model of 6 axes would comprise 800 multiplications, 600 additions, and 12 trigonometric functions which put it out of reach for the microcomputer boards shown in Fig. 6.

Another very demanding part of the online signal processing is the inverse coordinate transformation converting Cartesian to joint angle references. Most important, integer arithmetic becomes impractical in view of the complex numerical operations and the accuracy required, so that the modular control computer had to be expanded. A solution was found by designing a very compact floating point vector processor card, based on the WEITEK chip set [4]. This resolved the problem by computing the six-axes inverse transformation for the VW-G 60, consisting of 50 multiplications, 10 divisions, 5 square roots and 20 trigonometric functions in about 500 μs.

The recordings in Fig. 11 show first, how a deliberately introduced discrepancy between the programmed trajectory and the actual target path to be followed is reflected in the sensor signal, and then how this deviation is corrected by sensory feedback. The ability of the control scheme to accurately track the path and even to recover from large discontinuities is rather good, considering the complexity of the complete system. Here too, the coordinate transformations were carried out by the vector processor. For stability reasons, the sensory feedback loop was operating with 2.5 ms sampling period.

**Continued Work**

The distribution of duties to the various parts of the decentralized robot control described proved effective and balanced in terms of sharing the computational load. In particular, such a system has the advantages of all modular schemes that it can be expanded according to changing requirements; for instance should the installation of a new complex sensor become necessary, it could be integrated into the system by simply connecting it to another one of the control computer boards operating on the common bus.

More recently the work described has been applied to a robot of more modern design, a MANUTEC r3, having a 1.5 m radius and a payload of 15 kg. It is driven by six synchronous motors with lower gear ratios so that the dynamic coupling between the axes is accentuated. Most important, the signal processor based modular computer was replaced by an up-to-date transputer network offering two main advantages: programming in higher level language (OCCAM) and floating point arithmetic throughout, while maintaining the computing speed. The dynamic parameters of the robot can now be determined by identification, when the robot performs certain motions during the testing phase [19] and the speed controllers are self-tuned. When finished, this could be an important advance for simplifying the difficult and otherwise time-consuming task of tuning the robot controls with its numerous parameters and interactive functions.

**Fig. 10. Dynamic position error of axis 2 during the test shown in Fig. 9 for different feed-forward schemes.**

**Fig. 11. Measurements using a hand-held optical sensor.**
Conclusion

High performance control of multi-axes robots belongs to the most demanding earth-bound control tasks, because such plants combine great complexity with high required accuracy and speed of response. It is shown in the paper that these conditions can be fulfilled with microelectronic components. In view of the rapid technical evolution, the situation is in a transient state, where many details are obsolete by the time they can be reported. However, even with further technical advances the proven structure of decentralized and modular control will be upheld.

References


Werner Leonhard was born in 1926 in Germany. He studied electrical engineering at TH Stuttgart, receiving the Dipl.-Ing. and Dr.-Ing. degrees in 1951 and 1954. He joined Westinghouse Electric Corp. in Pittsburgh, PA, where he contributed to the development of controlled drives and static logic devices. In 1959 he continued at Siemens, Erlangen, working in the field of automation. In 1963 he became Professor of Control Engineering at the Technical University Braunschweig, also serving terms as Head of the Electrical Engineering Dept., as Dean of the Mechanical and Electrical Engineering Faculty, and as Chairman of the Coordinating Committee of German Electrical Engineering University Departments. He was the originator of the first two IFAC Symposia on "Control in power electronics and electrical drives" in 1974 and 1977 and Co-founder of the European Power Electronics Conference (EPE). He received the Eugene Mittelmann Award of the IEEE-Industrial Electronics Society in 1986, an honorary degree by the Free University Brussels and the VDE-Ring of Honour in 1988. Dr. Leonhard, who is a fellow of the IEEE, has published numerous papers and 7 books on various aspects of control and has been advisor to more than 500 Dipl.-Ing. and 60 Dr.-Ing. candidates.

Doctoral Dissertations

The Pennsylvania State University, University Park, PA 16802

The Pennsylvania State University, University Park, PA 16802