SUPERVISORY CONTROL OF LARGE-SCALED MANIPULATORS IN SEVERE ENVIRONMENTS

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1 Introduction

Today it is economically feasible to apply computer control technology in making heavy-duty manipulators more automatic. A heavy-duty manipulator (HDM) is a machine designed for a manipulation task performed in a severe environment such as a construction site, a dock, a forest, or a mine. Typical HDM is a large-scaled vehicle having an arm-like structure (Fig. 1). Each arm has several (4 to 7) independent joints. While an industrial robot is versatile, capable of performing a variety of different tasks by reprogramming, HDM is often designed just for one type of manipulation. Typical tasks are rock drilling and handling of heavy material.

Because of the unstructured and time-varying environment HDM cannot have totally autonomous control, but the control task should be shared by both human and computer. The human takes care of the most high-level parts of the control functions and the computer is responsible for low-level and repeatable subtasks. An important research issue is the design of the tightly coupled human-computer interface.

The moving of the large arm causes changes in the dynamical properties of the arm. Especially the picking up of a heavy item causes a sudden step in the loading conditions. The aim of the automatic control of the manipulator movement is to make the arm follow a certain prestored path as accurately as possible with smooth movements. Large variations in the loading conditions makes the path serving the most difficult problem.

In the course of the years, a major objective of the work at the Electronics Laboratory has been to adopt modern microelectronics into making HDMs more automatic. The emphasis of the work has been to overcome the problems related to the joint control, namely to achieve a smooth movement

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and to develop suitable computer-based instrumentation to support the digital control approach. In addition to the servo control, the role of the human-computer interface has been recently stressed. A new model-based interactive programming method based on the use of a laser pointer has been developed. To verify the results of the studies an experimental environment has been developed on the basis of a large-scaled loading manipulator, equipped with a computer-control instrumentation. The aim of the present paper is to give a short survey to our work at the Electronics Laboratory.

2 Research Facilities

Handling of heavy material is a typical task for a large-scaled manipulator in many working areas, including construction sites, docks, harbours, forests, and even on many production lines. The initial and final positions of the objects, which are to be manipulated, define the loading task. At both ends of the transfer movement the machine actions, grasping and releasing, are activated. The loading task resembles in many respects drilling which is another typical example of a heavy-duty task. The main difference is the tooling, instead of grasping drilling is activated at the end of the transfer movement.

A research environment for a log loading manipulator has been developed to study the intelligent controls of large-scaled manipulators. The manipulator is placed in a large experimental hall, which makes it possible to manipulate logs of normal size. The obstacles of the scene have different kinds of appearances. Natural obstacles are, for instance, walls and parts of different constructions.

The mechanical construction of the manipulator arm is based on a typical log-loader (see Fig. 2). The manipulator has six degrees of freedom which are activated by hydraulic cylinders and controlled by proportional type valves. The manipulator can handle large and heavy objects (max payload 300 kg). Due to great load variations, the dynamic effects have an important meaning in controlling the endpoint of the arm.

The computer network has primarily two level hierarchy: the execution and background levels. The executing control of the manipulator is implemented using a multiprocessor system as the main controller and distributed processor network for preprocessing the joint sensor data. The intelligent sensor modules are designed based on a single-chip microcomputer. The sensor module has three types of functionings: sensor signal interfacing, data preprocessing, and communication with the master.

The manipulator can be operated using several different kinds of modes. There are two manual modes: the operator may control each joint independently using the two joy-sticks or he can lead the endpoints of the arm in a Cartesian space while the computer calculates the necessary set values for the joint controllers (so called resolved motion control). A transfer path can be programmed into the computer memory by leading manually the arm through the desired path and storing the values of the joint data, or by specifying the desired path points by symbolic commands. The menuboard, which can be seen in the system diagram in Fig. 2, is used when giving the symbolic commands.

3 An Approach to Model-Based Interactive Control

In addition to the conventional way of programming the manipulator, a new approach has been taken to make the programming task easier for the human operator. The developed method is based on the use of a computer representation of the machine environment, which is called a scene model. The model makes the control of the manipulation task totally independent of the machine. The human operator is mainly responsible for the performance of the desired task rather than steering the machine. Thus the approach taken can also be regarded as task-level programming. The human operator is also responsible for the correctness of the model.

In Fig. 3 there is shown an illustrative diagram of the basic idea of the model-based approach. The role of the human operator is two-handed: to initiate the system and to monitor the performance. The initiation phase includes two functions, namely to preprogram tooling actions and to create the scene model. The operator monitors the performance by perceiving the task environment and by verifying the scene model. He commands the manipulator by instructions, which are related to the manipulation task. The role of the computer is to interpret the commands, to plan the machine movements, to control the execution, and to show the state of the scene model to the operator by picturial means.

The proposed model-based method emphasizes the following research issues: the design of suitable aids for the human-computer communication, the studying of suitable representation schemes for the scene model, and the development of methods for automatic planning of machine movements. A communication method based on the use of a laser pointer closely connected with a menuboard has been designed and a representation scheme to support the communication and the planning of machine movements has been selected. An algorithm to plan collision-free paths has been developed.

The pointer is used for measuring purposes. The operator aims the pointer to a target and stores the coordinates of it simply by a push button. The geometrical shape of a particular object (or obstacle) is modeled so that the operator selects a suitable geometric shape primitive from a menulist and measures the actual parameters of the object by the pointer. A geometric model of the whole environment is rapidly created by the proposed where method the human intelligence is used both in perceiving the scene and in promoting the interpretation of the scene measurements. The key element of the method is the laser pointer. It is capable of measuring the coordinates of the target with an accuracy of 10x10x10 mm, at the distances of 1.5- to 10- meters. The measuring time for one spatial point is 10 ms.

The automatic planning of the machine trajectories is based on the model interactively created. The aim of the trajectory planning is to compute a collision-free transfer path from the initial state to the target state so that neither the load nor the machine parts do collide with the scene obstacles.

The scene obstacles are modeled as convex polygons. The objects, which in our experimental system are logs, are presented as cylindrical items. When the object models are created, the grasping point of each modeled object is also automatically calculated. The planning of collision-free trajectories is done in two phases: first, a transfer path for a particular object is determined and second, the movement of the manipulator is planned along the transfer path.

An orthogonal projection of a scene model is shown in Fig. 4a. The initial state (S) and the final state (T) of the object (A) can be seen in the picture. The contour lines of the three obstacles B_1, B_2 and B_3, represent the heights of the obstacles (B_1 = 1.5 m, B_2 = 1.0 m, B_3 = 2.8 m).

To carry out the path planning, the original space is transformed into a topologically equivalent where space the planning problem is easier to solve. In the Fig. 4b there is shown the equivalent space and a transfer path. The path is a connection of straight line segments. The distance of the path to the obstacles is adjustable by a computational parameter.

Our experiments have revealed that the path planning can be computed in a fraction of a second and, therefore, it is also possible to implement in practical supervisory systems.

4 Adaptive Control in the Joint Level

In large manipulators, such as the one described in this paper, undergoing great load variations, the dynamical effects have great influence on the desired path accuracies. To solve such problems as insufficient rigidity, low natural frequency and low damping requires the consideration of the structural dynamics when designing a suitable motion controller. The approach used here to model the manipulator involved both the rigid-body and flexible motion analysis. However, the real constraints, such as the computer size, processing time and required sensors set the limits for the model which can be used for control purposes. Therefore, a suitable compromise must be chosen between the constraints and the model accuracy. In our application the results of the analysis and the measurements showed that the manipulator flexibility could be modeled with reasonable accuracy by a few elastic degrees of freedom. Also, the first mode of vibration was noted to be dominating. The vibrational motion of the manipulator end-point was detected by the same sensor which was used to measure the manipulator load. The use of this external sensor guarantees that the model parameters can be updated according to the variations of the manipulator loads in real time. A scheme of the manipulator control model is shown in Fig. 5. The actuator control forces result from the rigid-body nominal forces $F_r(t)$ and the flexure control forces $F_t(t)$ as

$$F(t) = F_r(t) + F_t(t)$$

Both the rigid-body model and the flexible model make use of the load data $F_1(t)$. For suppression of the manipulator vibrational motion, the independent modal space control method was applied. Also, a static correction to the location of the manipulator end-point was calculated based on the developed flexible model. The compensation of the manipulator deflections was necessary because the yielding of the manipulator structure is several centimeters at the end of the arm.

5 Design of Joint Sensor Module

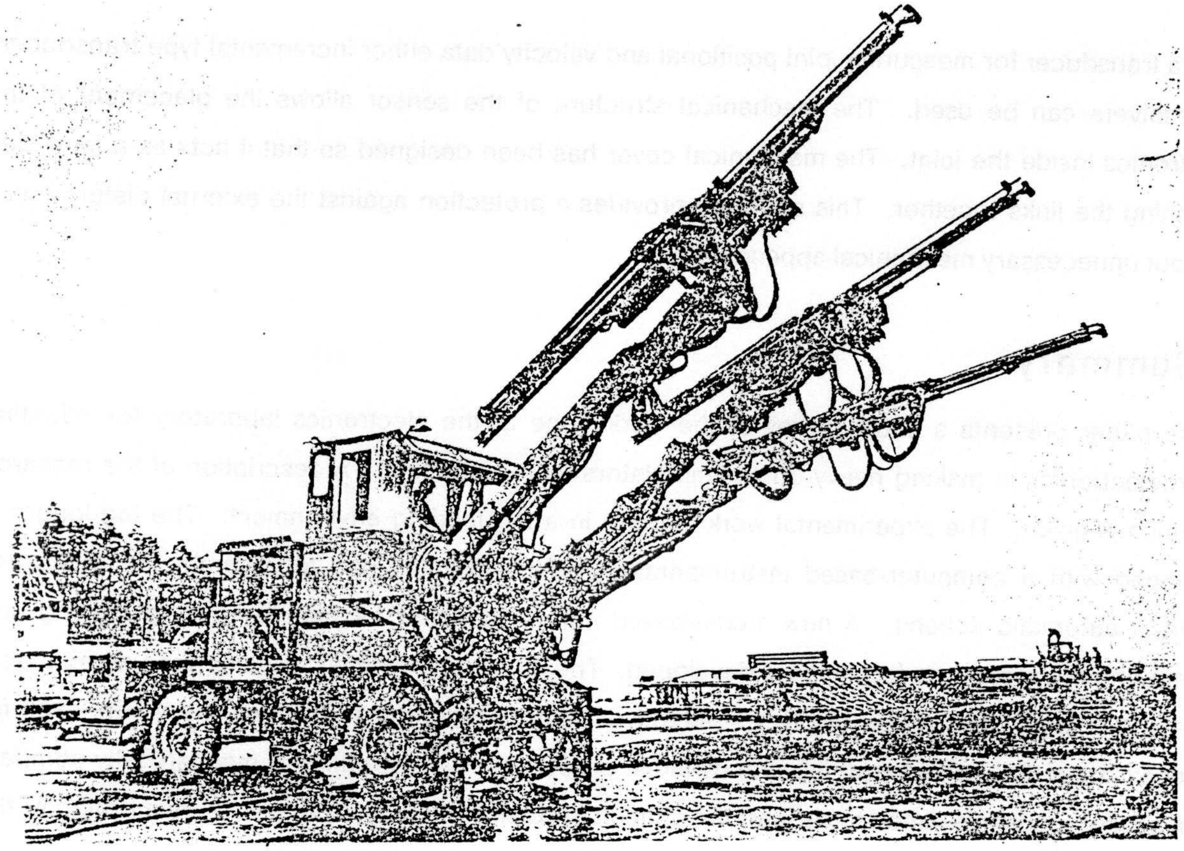
To realize the programmed trajectory the controller makes use of the measured data of the manipulator state. Conventionally, the state of the manipulator is determined by the sensors located in each joint. Although the direct measurement of the manipulator end-point would be in many respects preferable, the practical reasons have dictated the use of joint sensors. However, the protection of the measuring transducers, electronics and cables require the mechanical design of sensors such that the external shocks or collisions do not damage the sensors. Therefore, an intelligent sensory system was designed to test the practical questions of the applied techniques. The joint sensors form a distributed multiprocessor network which use common serial interconnection for data transmission to the center computer.

The serial connection allows a simple way for data transfer and diminishes the wiring between the sensors and the control unit. The local intelligence in each joint also offers possibilities for transducer interface control, timing, and preprocessing of the transducer signal for relieving the higher level computer from simple data manipulation operations. Each joint sensor module consists of separate units as line interface, processing unit and transducer interface. The line interface is based on usual RS-232-C standard.

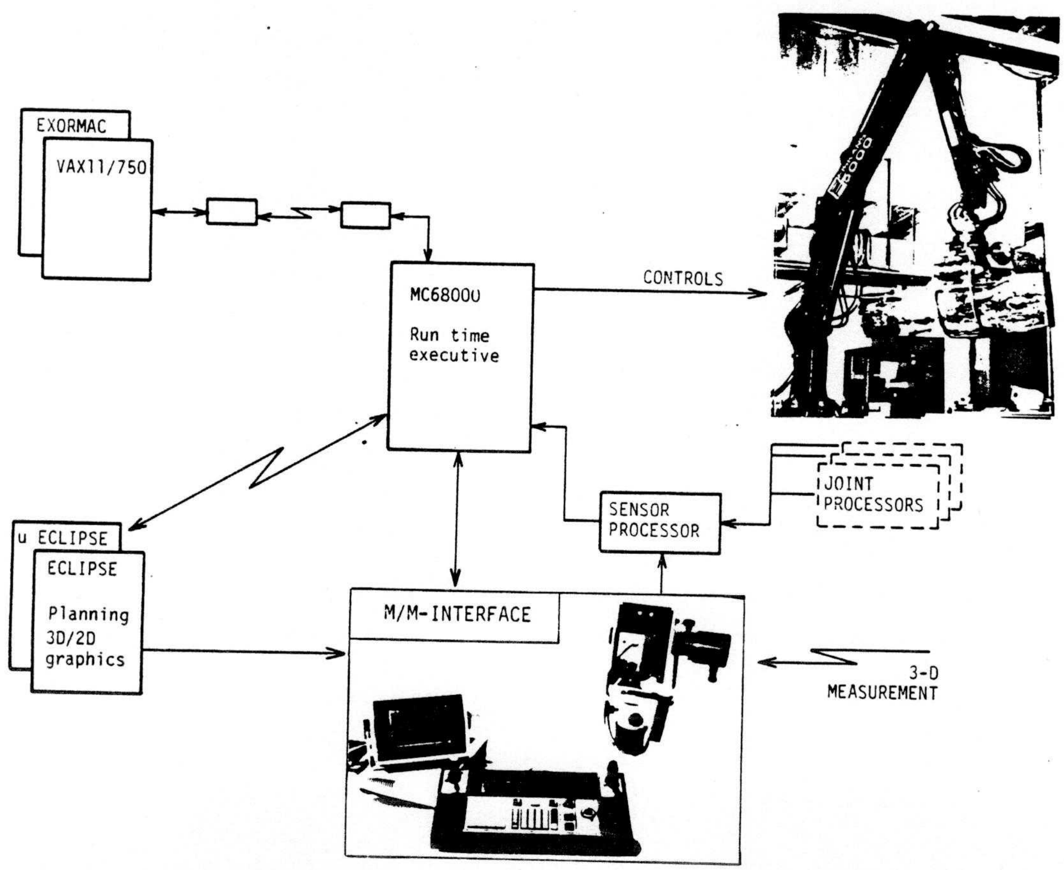
As a transducer for measuring joint positional and velocity data either incremental type transducers or resolvers can be used. The mechanical structure of the sensor allows the placement of the electronics inside the joint. The mechanical cover has been designed so that it acts as a joint slab attaching the links together. This structure provides a protection against the external disturbances without unnecessary mechanical appendices.

6 Summary

The paper presents a short survey of the work done at the electronics laboratory for adapting microelectronics in making heavy-duty manipulators more automatic. A description of the research facilities is given. The experimental work is done in a log loading environment. The log-loader is equipped with a computer-based instrumentation, which enables one to program the system to perform automatic actions. A new model-based control concept for high-level programming and monitoring the system performance is developed. The developed method relies on the use of a laser pointer. Finally the paper discusses adaptive control algorithms used in the joint level for compensating the variations of the arm dynamic properties. The design of a mechanically compact joint sensor module is aimed to support the difficult problems of the arm control. A description of the module is given.



Rock drilling machine.



2.   Diagram of the research environment

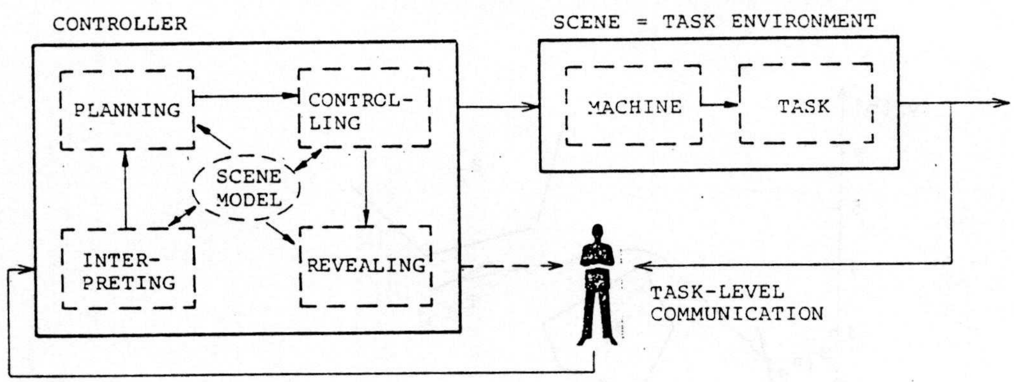


Figure 3: Illustrative Diagram of the Approach to the Interactive Control

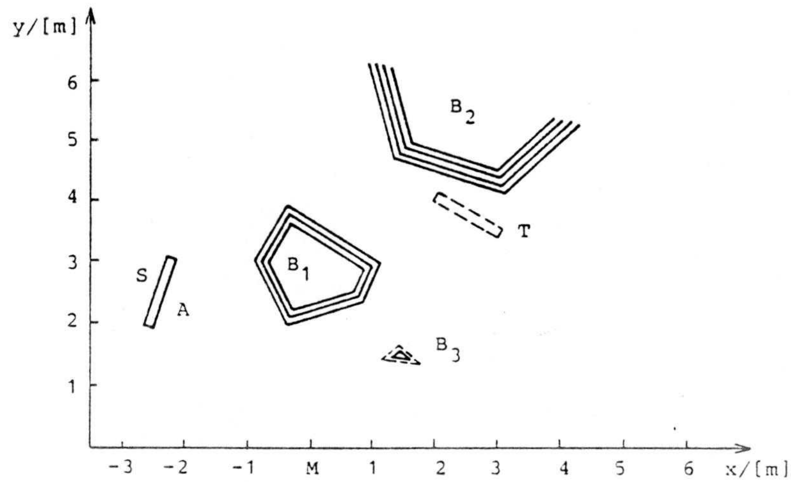
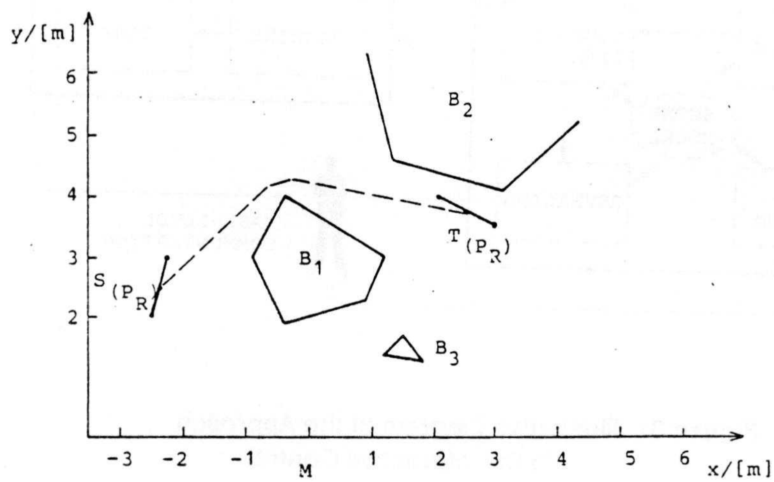


Figure 4: a. Orthogonal projection of a scene with three obstacles (B_1, B_2, B_3) and with an object (A The initial state (S) and the target state (T) of the object are also shown.



b. The transformed form of the space (a), where the planned trajectory is also shown.

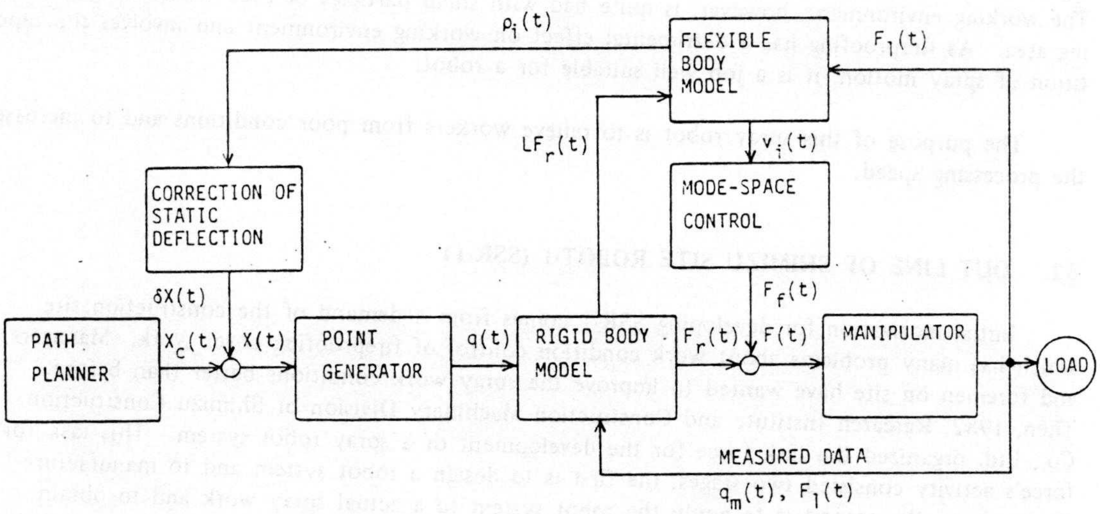


Figure 5: The control model of the manipulator