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PHYSICAL SIMULATION OF FLEXIBLE MANUFACTURING SYSTEMS

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The physical simulation capabilities of the Manufacturing Systems Laboratory are presented. The benefits of physical simulation are briefly noted. A Fischer-Technik based simulator of a flexible manufacturing cell is explained in detail. Plans to integrate computer-aided-design (CAD) into the modeling process are discussed and small robot physical simulation facilities are described. After relating some of our experiences and plans, we explain how the Manufacturing Systems Laboratory objectives achieve some of the benefits of physical simulation.

INTRODUCTION

Currently a major emphasis is in the design of a flexible manufacturing cell utilizing the Fischer-Technik modeling components, a hierarchial Local Area Network (LAN) of microcomputers and a programmable controller, and specially designed interfaces. A second thrust is in performing simulations using small robots.

It is important to distinquish the difference between the concepts of a simulator and simulation. In the field of computer simulation, the simulator is the logical model developed using one of the many simulation languages. A simulation is running this simulator on the computer to obtain information on the model's performance. In physical simulation the simulator is a scaled replica of the real system. A simulation is then the actual operation of the model system to gain insight into its performance. Both approaches are used to understand better the expected performance of the real system and to test the effectiveness of system design. One needs to consider each of these concepts to differentiate the utility associated with each approach.

The primary emphasis is on the development of physical simulators to replicate flexible manufacturing systems. Our primary use of physical simulation so far has been limited to the demonstration of the simulators.

In the next section we discuss the benefits of the physical simulation approach and in successive sections present a description of a flexible manufacturing cell simulator, the integration of computer-aided-design (CAD) into the modeling process, a brief discussion of plans for small robot simulations, and a review of our experiences and plans. In the final section we delineate our objectives and relate these to the benefits of physical simulation.

BENEFITS OF PHYSICAL SIMULATION

There are two major categories of benefits: proving design feasibility and education. Although the use of physical simulation to study manufacturing systems is relatively recent, there is a long history of its use in other fields of design. Two impressive examples are in Water Reources and Aeronautical Engineering. In the early thirties, the Corps of Engineers constructed a model of the Mississippi River at the Vicksburg Waterways Experiment Station. This model has been used over the years to test and validate designs for dams, channel improvements, and diversions. Which test pilot would volunteer to fly a newly designed airplane if the wing design had not proved feasible in a wind tunnel simulation?

The benefit of proving design feasibility of manufacturing systems is the same as in the above examples: the avoidance of costly design errors. The expense of simulation studies is analogous to buying insurance. In most years the insurance is not needed, but if it is needed all previous premiums have been worthwhile. A physical simulation of a particular manufacturing system may only demonstrate feasibility. But if such a simulation indicates the need for a major redesign, the expense of supporting this capability will pay for itself. For instance, one company, in the business of designing and constructing plants, discovered that a major facility had been misaligned due to a drafting error while constructing a Fischer-Technik model. If the plant had been constructed it would have cost an estimated $800,000 to correct the error [1].

The construction of a physical simulator can suggest improvements in design of the system by viewing the spatial relations between machines, transfer mechanisms, and material handling equipment. Physical Simulation (operating the manufacturing system model) can identify opportunities for better product flow and sequencing alternatives. Thus physical improvements are identified.

A computer simulator and simulations determine the need for changes in capabilities of system components and in this respect are superior due to the inherent inaccuracies in physical models. But computer simulation does not identify the physical solution to the problems it uncovers. Thus, in the opinion of the authors both simulation approaches are needed to help ensure design feasibility.

The educational role of physical simulation is twofold:

1. To provide a communication tool for the manufacturing system design group in helping management to understand the benefits of advanced technology.
2. To teach prospective engineers an understanding of the complexities of Computer Aided Manufacturing (CAM).

Managers at all levels are usually well read in the benefits of flexible manufacturing systems but often lack the understanding of the technical ideas to be fully supportive towards implementing these systems. Viewing a physical simulator which can reproduce the operation of the system, may be the instrument through which a manager becomes fully supportive. It is well known that tables and graphs resulting from computer simulation do not achieve a high level of confidence, primarily because the underlying simulator can not be assimilated in the time available. This fact is underscored by the emergence of many expensive computer simulation systems emphasizing animated color graphic representations of the simulation (e.g. see [2]). Physical simulators increase the manager's perception of the system and afford him with the opportunity to make suggestions, thus drawing him into a closer identification with the system.

The second educational role is obviously the primary focus of the authors of this paper. Designing, constructing, and testing a replica of a manufacturing facility provides the student engineer with the opportunity to use the basic engineering theory studied in the formal classroom and gives him/her a better understanding of the application of theory. The requirement to integrate the model with computer control is instrumental in teaching the concept of an integrated system. The student must consider the timing and sequence of motion on different axes, the role of limit switches and feedback sensors, the constraints of interface and component design, load and unload cycles, workpiece holding, and the realities of computer control programming. The need to integrate this facility system as a subsystem to a larger system, such as a manufacturing cell or plant reenforces the system concept.

For a more detailed discussion of the benefits of physical simulation see [3].

THE STRUCTURE AND CONTROL OF AMANUFACTURING CELL SIMULATOR

The physical simulator is a scaled down version of the Manufacturing Cell being developed at the College of Engineering's Advanced Manufacturing and Robotics Center. Machine models are constructed from Fischer Technik modeling components and simulate machine motions and processing sequences. The cell, in its present configuration, consists of a Horizontal Boring Mill (HBM), a Machining Center (M/C) and a Coordinate Measuring Machine (CMM). The material handling system for the cell consists of a robot on tracks. The physical layout of the cell is illustrated in Figure 1.

The Fischer-Technik models reproduce the axes of motion as is existent on the actual machines and are sequenced through their motions by means of a machine controller. There are two types of controllers being used:

1. An Allan Bradley PLC2/15 programmable controller, and
2. A Commodore 64 computer with a specially designed interface.

System Description

The Allen Bradley Programmable Controller (PC), is programmed using sequential logic and is used to sequence the HBM and the CMM through a series of machine cycles, in correspondence with the operation sequence for the part in question. Multiple operation sequences for each machine may be programmed into the PC for each machine and these may be executed as is necessary.

The Commodore 64 computers are used as a control device by making use of the capabilities of the expansion port wich has 512 addressable locations. A special interface nas been developed which fits into the expansion port and provides six axes of motor actuation and feedback. In addition, there are 32 bits available from two 6522 PIA's which can be configured as input/output lines used for reading or activating switches. The RS-232 (user port) of the Commodore is used to link up other computers in a communication mode. The C64 is programmed in BASIC to control the Robot and the Machining Center. This configuration provides for flexibility of machine programming akin to a CNC machine.

The link between the PC and the C64 is achieved by utilizing bits from the PIA's to turn on and turn off the required machine cycles. References [4] through [14] were useful in designing various aspects of the system.

The C64 Interface

The C64 interface plugs into the expansion port of the C64 and consists of six Pulse Width Modulated (PWM) signal generators each of which can be turned on or off separately, polarity reversed, or the duty cycle varied. These signals are fed to a driver board which

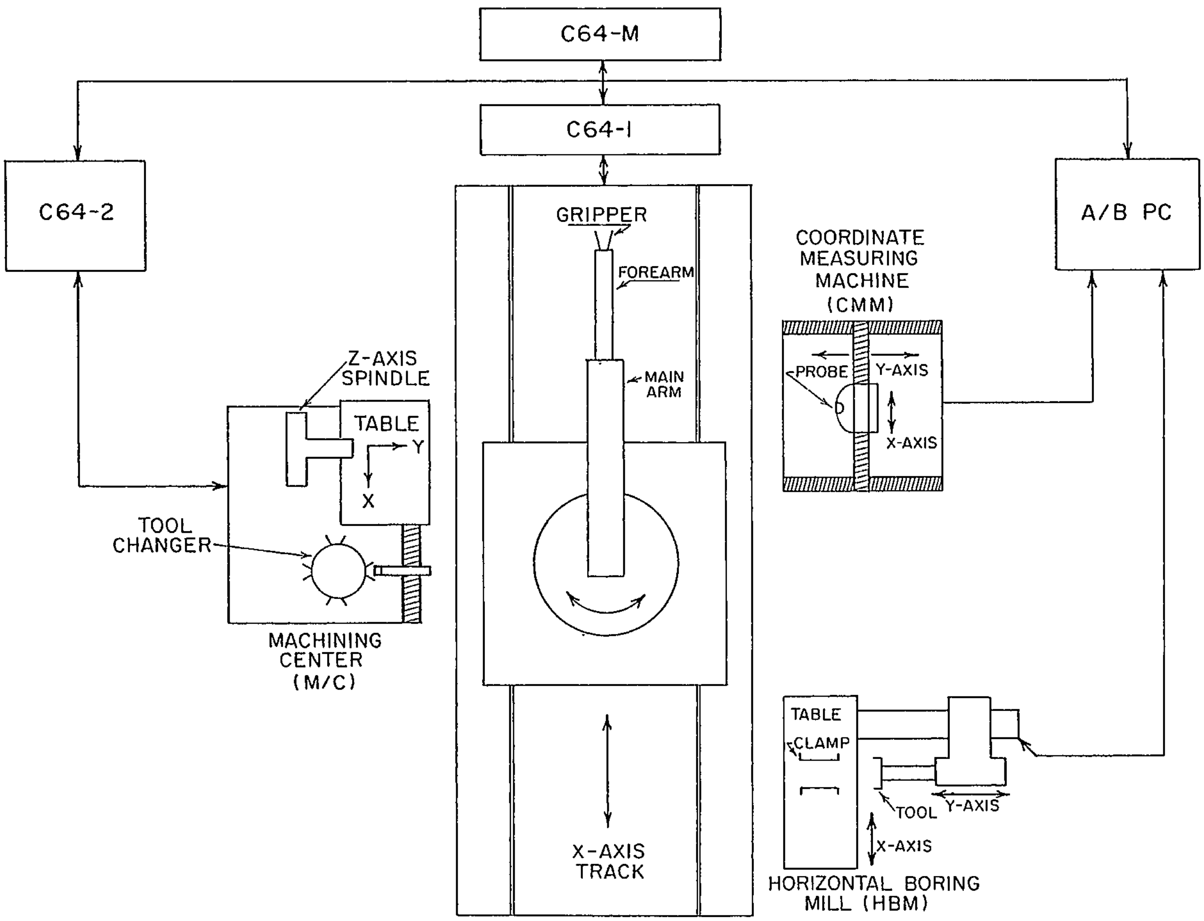

Figure I Flexible Manufacturing Cell Layout

are used to drive the motors of the Robot or Machines. The Interface board also has six feedback boards which are connected to optical pickups on the Robot/Machine, the pulses generated by the pickups are used to update a comparator on the feedback board which controls the PWM output for the required motor.

The bits from the 6522 PIAs can be configured as inputs from limit switches or emergency switches or outputs to other devices such as system sensors. A block diagram representation of the system is shown in Figure 2.

Allen Bradley Interface

The Allen Bradley Programmable Controller Interface was specially designed to drive the Fischer-Technik D.C. Motors, and sense the limit switches on the machines. This interface also provides for direction control of the motors, regulates the voltage to 15v d.c.. and easy to use plug-in input/output ports which are compatible with the Fischer-Technik system.

System Logic

The existing system is provided with a user Interface which provides the operator with the capability of scheduling the robot through a sequence of moves, e.g. input subsystem to the HBM, HBM to the CMM, CMM to the output subsystem. Delays may be introduced between moves or a competion indicator signal from the machine may be used to activate the robot through the next sequence. The robot controller, after loading a machine, sends a signal to the Allen Bradley PC to set the machine in operation. The keyboard buffer of the C64 can be used to store a sequence of robot motion codes which are executed in series. This provides the robot flexibility in servicing other tasks while it is waiting for a particular machine to finish its cycle. The user Interface also provides a manual option which can be used to guide the robot through any new sequence.

The M/C also has its own C64 to control its operation. The machine has a tool rack, a Tool Changer, an X-Y Table and a Spindle which simulates feed and speed movements. There are optical feedback paths for the X-Y Table and the Tool Rack. All other motions are defined by the status of limit switches. The complexity of control of the machine justifies the dedication of a C64 for its exclusive control. The machine controller is initialized during start up with the necessary algorithms used for machine movements. The parameters for the execution of the required algorithms are entered via the keyboard or can be sent via the Pseudo RS-232 line which links the different controllers. This link forms the basis of the local area network. The programming language being used is BASIC and all the actuation and feedback functions are achieved by accessing the required control registers on the interface board by means of Poke and Peek BASIC statements. These statements are programmed into subroutines which define the elemental motions of the robot or machine. Depending upon the robot sequence or machine cycle required, the necessary parameters are passed and the subroutines are linked together.

The Local Area Network

The diagrammatic representation of the local area network being developed is shown in Figure 2. The C64-1 (computer number one) is the robot controller. This controller is dedicated towards sequencing the robot. The C64 Interface is used to perform the required functions while the Pseudo RS-232 port of the C64 is used to link the controller to the Master C64 (C64-M).

During startup, the C64-M is responsible for coordinating the loading of the C64-1 with the control programs. During the manufacturing phase, the C64-M monitors the status of the robot (Busy/Not Busy), the HBM and CMM via the programmable controller, and the M/C via the C64-2. It is also responsible for passing the required parameters for execution of the control programs. This would typically contain the following information: sequence code, machine number, and the machine cycle number. The Master will also read from the C64-1 the status of the robot, the status of the machines, and current location of the robot. This is achieved by reading the configuration of the 32 bits available at its C64 Interface.

During any communication cycles between the Master and the Slaves (C64-1 or C64-2), the Master has to relinquish any monitoring or control functions it is performing. It is thus necessary to incorporate Emergency Stop routines at the level of the Slaves to safe guard against any low level system failure. Since the majority of the communications which are time intensive take place during system startup this is not yet a serious problem.

C64-2 is the M/C controller. Its functions are to activate the machine through all of its motions, keep track of the tool rack position, generate appropriate table motions and also control the tool motion. The controller is provided with the necessary

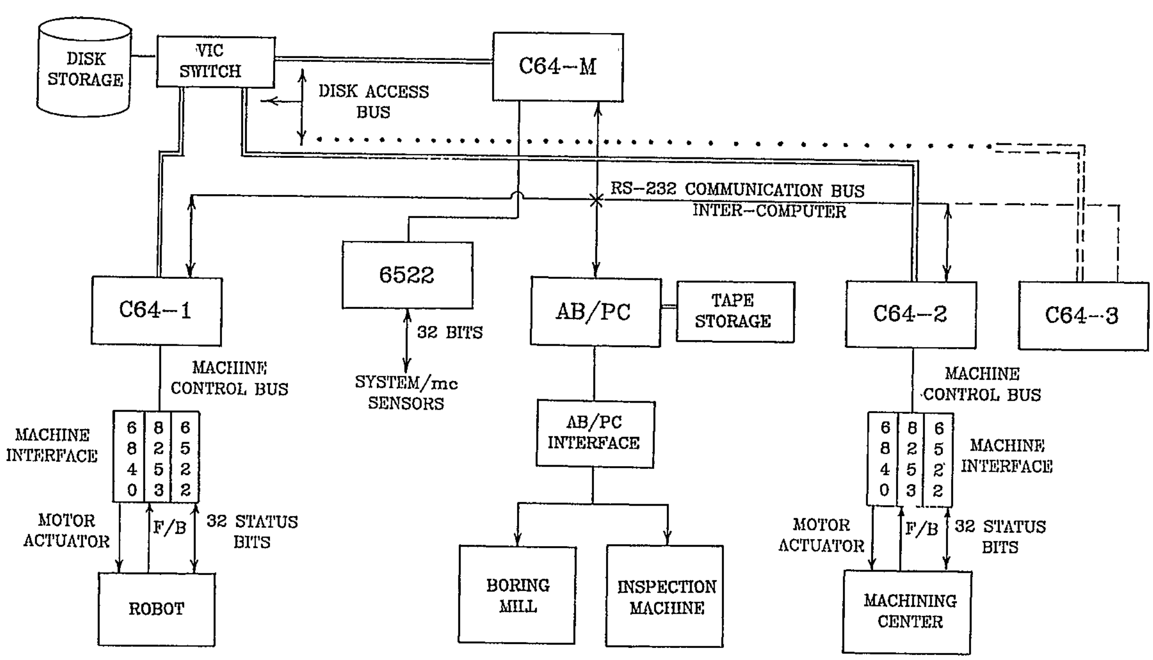

Figure 2 Local Area Network and Interfaces

algorithms to perform these tasks, and these are activated by parameters which are passed down from the C64-M. The data requirements for this are: tool number, table motion code, and feedrate. The Master Controller can be operated either from a Data File or can be treated as an operator's console from which the necessary operations can be entered.

There is a single disk drive at the master level which serves all the computers. The loading of the lower level computers can be achieved either through the Master or by the use of VIC-Switch.

Purpose of the Simulator

This simulator, which is constantly being redesigned, can be a very instructive educational aid in the areas of developing algorithms for control of actuators and machines, machine sequencing algorithms, and hardware improvements for networks and communication. It is useful for studing the effect of machine layout on scheduling and the effects of mixed part scheduling on the cell performance. It is a real experience in interfacing different technologies and a visual experience in FMS performance.

At present most of the status bits from the 6522's are not being utilized and these can be looked upon as hooks for system expansion. The individual bits can be used to sequence independent monitoring or control systems which may be other microprocessors controlling subsystems such as a conveyor system, a temperature or tool wear sensor, etcetera.

CAD AND PHYSICAL SIMULATION

One problem experienced by a number of individuals using physical simulation is the excessive amount of time taken to construct the models. A computer-aided-design approach to attempt to overcome this problem is being implemented. We are in the initial stages of a four phase project to use CADAM on an IBM 4341 computer to design Fischer-Technik models.

In the initial phase a file of drawings of the Fischer-Technik components which are most commonly used in the construction of a manufacturing facility is being built. We have developed a categorization of these components which groups the parts by logical use. Each of these groups are a menu describing the components within the group. Each component drawing will become two or three "details", (depending on symmetry), contained on a page keyed to the menu.

At any point of the design process, a detail can be called to the screen by referring to the menu and/or the page index. By selecting two points on the detail and then specifying these two points on one view of the master drawing, the designer adds this component to that view. The designer must add the component to all three views. By systematically adding a coded note, a bill of materials can be obtained from the finished drawing.

The designer can store partial designs to explore alternative solutions to a particular design problem. We are also investigating methods of transferring the two dimensional views developed in CADAM to obtain three dimensional representations of the model using CADIA.

The use of CAD is viewed to work in the following way. The potential model builder, having gained some experience with Fischer-Technik components, will prepare a sketch of the manufacturing facility to be constructed. He or she will then go to a CADAM terminal and prepare a preliminary drawing. A hard copy can be obtained from the graphics printer in the Computer Aided Engineering Center and in addition the drawing can be viewed on an IBM 3279 terminal in the Laboratory.

Using the computer generated BOM, all the components can be obtained from the parts drawers and placed at a workstation. The model can be constructed from the drawing with any additions or changes sketched onto the hard copy. When the model has been constructed satisfactorily all changes made during construction can be added to the drawing so that the model structure is fully documented. Then the designer can call from memory drawings of the computer and the feedback interface from which a wiring diagram and electrical specification plan can be prepared. Returning to the Laboratory, the electrical control for the model can be incorporated and tested. Again any changes made in the Laboratory will be entered at the CADAM terminal so that the control system wiring is also fully documented.

Drawings and explicit procedures for developing the control system wiring are planned for Phase III of the project. Phase II of the project will be the development of templates and files of various facility subsystems which can be incorporated into the final design. For instance, we have already designed several alternatives for X-Y tables, which when placed in a computer file, can be used as the basis for designing a machine which requires such a table.

Phase IV, the final phase of the project, will be the development of a file of drawings of complete manufacturing facilities which can be used to study layout problems and prepare layout drawings. Once we develop a file of a variety of machine tools and material handling equipment, it will be possible to prepare alternative designs for flexible manufacturing cells and systems. Given time constraints and our use of student learning projects, the completion of this project as currently planned is probably about a year away.

Several benefits to the Laboratory itself are hoped to spin off from this project. One will be that the drawings will be incorporated into the student's final report. A comparison of the drawing to the physical model will aid the professor in determining a grade on the attention to detail in the student's documentation. The BOM for each completed facility provides a record of where components are. By using the BOM with Fischer-Technik part numbers as an attribute, we hope to develop an inventory ordering and control system.

SMALL ROBOT SIMULATORS

The Manufacturing Systems Laboratory has one Microbot Teachmover, two Heathkit Heros, and two Rhino SR-2 small robots. The Hero robots have been used in one Industrial Engineering course as an introductory robot programming experience. This robot was selected to give the students the opportunity to work both with robot motions and sensors. The recently purchased Rhinos will replace the Heros as soon as we have integrated sensing capabilities into the control system. The microbot has been used for various student projects. Perhaps the most interesting project was to simulate robotic pick and place off a moving conveyor (constructed from Fischer-Technik components).

So far the number of projects using small robots has been limited by having only one Apple computer available. This activity is increasing with the addition of two Apples and an IBM PC last summer. With the exception of the project mentioned above, the use of these robots in physical simulation has been limited to their role as simulators of real industrial robots.

Last summer a continuous, variable speed conveyor was constructed and integrated with the Rhino control system. We are in the process of adding force sensing feedback to the control system. Several physical simulation studies of robotic assembly lines are planned. One involves the use of a single microcomputer to control simultaneously the operation of the two Rhinos and the conveyor speed for two successive tasks of unequal length. A second project will emphasize communication design problems by using two micros for essentially the same task. Pending the outcome of these studies we hope to initiate studies on cooperative robots, that is having two robots work together in the way that man's two arms and hands work together.

We have a GE vision system which is currently being used in conjunction with our IBM 7565 Assembly Robot. It is mounted on a transportable cart and is available for integration into a physical simulation project using our small robots. No specific studies have yet been planned.

EXPERIENCE AND PLANS

Every two years the College of Engineering holds an exposition where students prepare exhibits illustrating engineering technology. This three day event attracts high school students within a radius of about a hundred miles and thousands of the local populace. For the 1979 Expo. a group of I.E. students constructed an Automatic Storage and Retrieval System. A group of M.E. students constructed a computer controlled transfer line for the 1981 Expo. In the Spring of 1982 an I.E. student designed and built a three axis robot with an electomagnetic end effector controlled by a Micromint Z80 single board processor. This robot consisted of a main and forearms mounted on a platform. The platform moved longitudinally on tracks driven by Fischer-Technik minimotors.

In retrospect, this initial model was the first instance of a situation we have come to accept over time. The Fischer-Technik modeling components often need to be supplemented by other types of components or specially designed mechanisms to accomplish a particular design objective. In this case it was found that the Fischer-Technik motor did not have sufficient torque to move the main arm with all its appendages very efficiently. It was determined that a DC aerolon motor accomplished the task and was incorporated into the design. The weight of this motor helped solve an additional problem. Due to the length of the main arm (11.5 in.) and the forearm (10.5 in.) a large moment force results at the axis of rotation of the main arm. By locating this motor at the end of the main arm on the opposite side of the rotational axis it provided an effective counterbalance.

The Manufacturing Systems Laboratory had its start the next semester when a group of four students (ECE,IE,ME) began the project of incorporating the robot into a flexible manufacturing cell. The design solution selected to provide a rotational axis for the robot was to use a shelf organizer with built-in ball bearings to distribute the weight of the robot away from the axis. A Fischer-Technik chain was glued to the outside diameter so that rotational motion could be achieved by a motor and gear train.

The major lessons learned from simulations with this model include:

1. That an open loop control system is too unreliable for the robot to transport parts between machines due to the impreciseness of Fischer-Technik assemblies.
2. That computers need to be circuit protected because students will make wiring mistakes.
3. That cassette storage of programs for the Micromint Z80 can be frustratingly unreliable.

It took us nearly a year to overcome these problems. We performed a cost versus function analysis of several low cost microcomputers before selecting the Commodore 64 as our basic control computer. It was the cheapest computer which provided both serial and parallel ports, game ports which could be used for switching, comparatively low cost peripherals, and excellent system documenta-

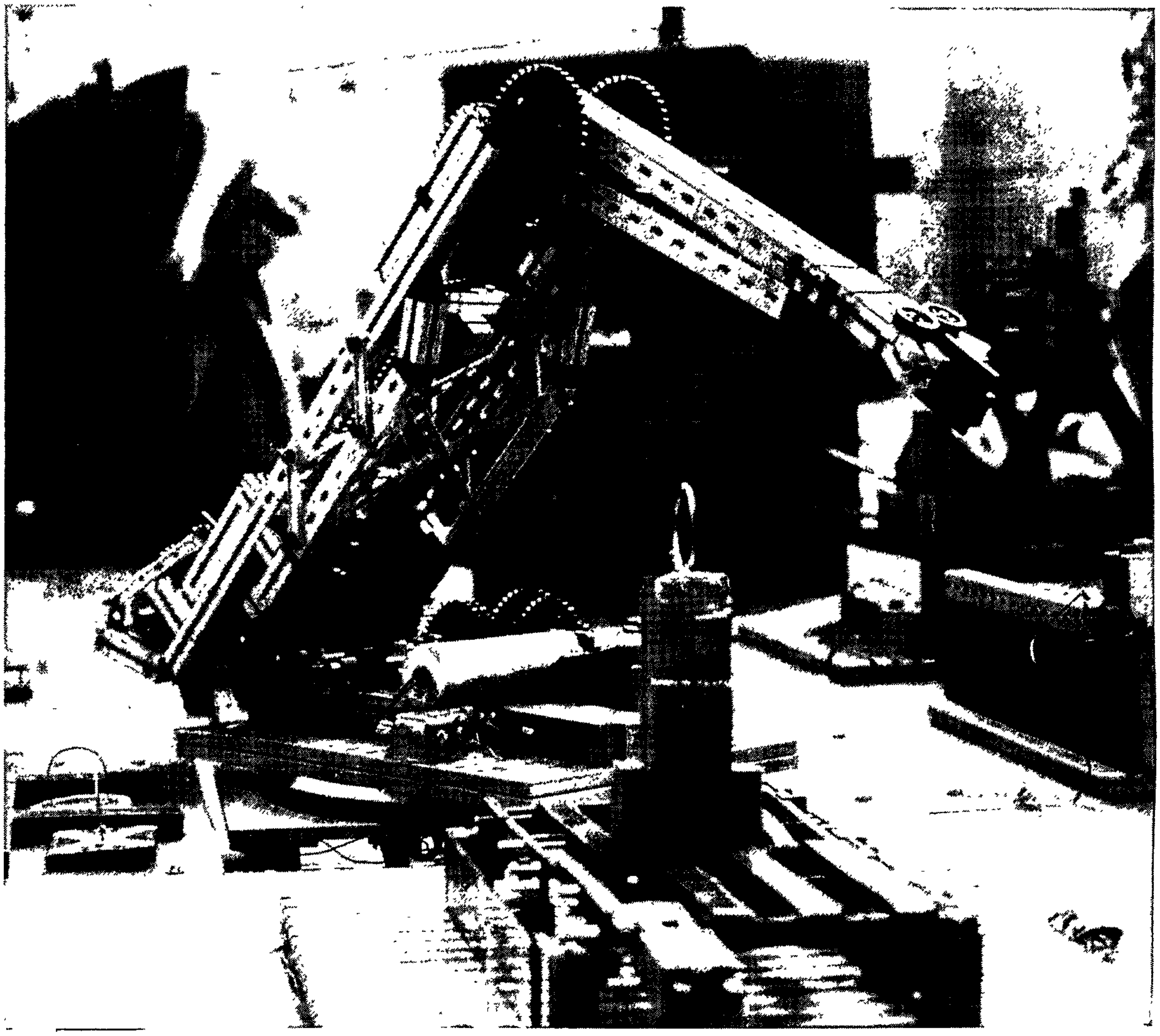

Figure 3 Fischer-Technik Robot

tion. The electonics shop went through two lengthy design iterations before arriving at the C64 actuator-feedback control interface described above.

Our current effort is to expand the system to include input and output conveyor systems with an Automatic Storage and Retrieval system and to incorporate additional machine tools through student projects. Our experience has shown that a one semester project provides insufficient time to both design and integrate a sophisticated machine design. Thus we are only allowing simple three axis designs for a semester project. Sophisticated manufacturing facilities will be accepted only as two semester projects. We have standardized the track mounting system for the robot and believe alternative robot designs are feasible within a semester. We intend to develop one of these designs with a standardized end effector mounting system to allow students the opportunity to design and test special purpose end effectors.

CONCLUSION

The objectives defined for the Manufacturing Systems Laboratory are for engineering students:

1. To gain a better understanding of CAD/CAM/LAN and have an elementary experience using these systems.
2. To learn about process control computers, interfaces and programmable controllers.
3. To learn the functionality of manufacturing facilities by building operating models of them.
4. To learn how to document a design project and gain experience in technical writing.
5. To provide the facilities for student research into flexible manufacturing systems.

Thus our primary use of physical simulation is to obtain its benefits in the role of training. We do have the capability to provide the first listed educational benefit: selling management on the technology of flexible manufacturing systems. The table for the flexible manufacturing cell was redesigned to be more transportable after one experience of demonstrating the system at a Board of Directors meeting in Milwaukee. We are a regular stop on a tour for most VIPs.

Thus to date we have had little experience in using physical simulation to prove design feasibility. We have in essence built physical simulators of hypothetical systems. This is changing! With some modifications our manufacturing cell will be able to simulate the Flexible Manufacturing Cell being developed for our Advanced Manufacturing and Robotics Center. Several projects are being planned to study designs for proposed manufacturing facilities. One is to prove the technology of removing risers from castings for a foundry. Another is to prove increased productivity in flame cutting through an improved machine design suggested by a professor's research on this cutting operation. We feel that the Manufacturing Systems Laboratory is still in an early growth stage.

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