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A Development of Courseware for Mechatronics Education*

K. YAMAZAKI,†
Department of Mechanical, Aeronautical and Materials Engineering, University of California, Davis, CA 95616, U.S.A.

S. MIYAZAWA
Production Systems Engineering, Toyohashi University of Technology, Tempaku-cho, Toyohashi 440, Japan

In order to cope with the growing demand for Mechatronics engineers, the mechatronics-CAD/CAM Laboratory of Toyohashi University of Technology has been providing mechatronics engineering education since 1980. After experiencing an orginal implementation, an effectiveness of the education method has been carefully evaluated and 'mechatronics control' has been recognized as the most important part of mechatronics engineering. The courseware which consists of hardware and software so-called MCTS (Mechatronics Control Training System) for efficient education has been developed and implemented in the real classroom environment. The education using this MCTS has been found to be effective as a result of the evaluation.

INTRODUCTION

THE term 'mechatronics', which represents technologies to enhance a value of mechanical systems with microelectronics and computer science, has been becoming popular since the mid-70's when micro-processors were introduced into industrial control. This new integrated technology is still growing explosively in industries and engineers who can freely handle both electronic and mechanical technology are in great demand. In order to cope with this situation, universities and technical colleges should offer mechanical engineering students knowledge and experience in microelectronics applications to mechanical system control.

The Mechatronics-CAD/CAM Laboratory of the Production Systems Engineering Department at Toyohashi University of Technology has started a mechatronics engineering education program in 1980 and interactive activities among education, cooperative research with industries and dissemination have been conducted [1]. Based on the experience obtained in running the course of 'Mechatronics Engineering', the contents of the course and the teaching have been improved year by year. Recently, in addition to these improvements, new courseware has been developed, so that each student can learn with a custom made system, a so-called 'Mechatronics Control Training System (MCTS)' in a unique lecture-hands-on-mixed environment.

This paper describes the major technologies for mechatronics engineering, organizing a mechatronics engineering course and courseware developed.

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† Associate Professor.

CONCEPT OF A MECHATRONICS SYSTEM

A 'Mechatronics System' is, as the word represents, a system in which a mechanism is equipped with an electronic control. The system features a software control for a flexible motion which can be realized by a simple mechanism and a microprocessor based control system.

Figure 1 shows an evolution of a mechatronics system in terms of 'total added value' and time. Once a mechanism has been introduced, efforts are made to enhance the value of the mechanical

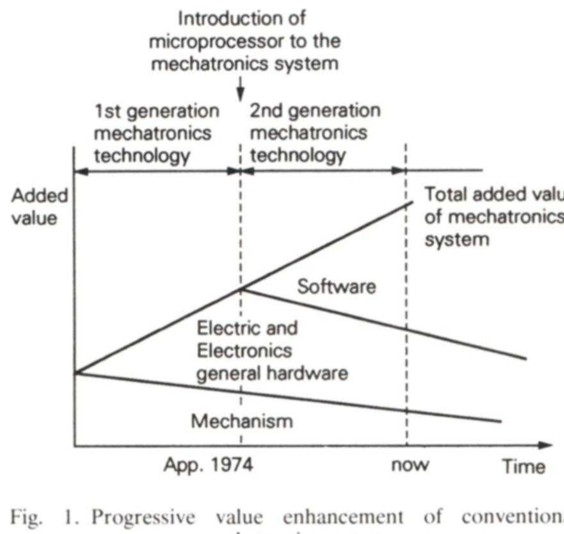

Fig. 1. Progressive value enhancement of conventional mechatronics system.

system, automating its operation and/or improving its performance. After the World War II, mechanical systems have been equipped with 'general electric and electronic hardware'. With this configuration, motion of a mechanism has been controlled by a hardwired controller. This was '1st generation of mechatronics' and lasted until the mid 1970s when the microprocessor came into use for industrial applications. While the first generation mechatronics system consisted of two kinds of components, 'mechanism' and 'electronics and electric hardware' (today, it is very common to find a mechatronics system in which more than 50% of a system's total value is occupied by 'electronics and electric hardware' as well as 'control software'.

One of the most important facts which a mechanical engineer should note is that as the mechatronics technology evolves a mechanism loses its value. In the past mechanical industries have depended on the electronics and electric industries to equip their mechanical products with electronics and electric controls. Today, many industries producing mechanical products are trying to provide those controls by themselves so that they can recover the decreasing value in the 'mechanism' by supplying an additional value on self-made controls. In order to achieve this goal, it is necessary to have mechanical engineers who can freely handle these three technology components. And those engineers should be educated and supplied by educational institutions. For establishing the education of this new field, 'mechatronics technology' should be identified as one of the academic engineering fields and a methodology for effective education should be organized.

ESSENTIAL TECHNOLOGIES FOR MECHATRONICS SYSTEMS

The most important feature of the mechatronics system is the flexible motion of the simple mechanism with a sophisticated control system. Figure 2 is an example of a conventional mechanism where the multi-axes motion can be controlled. A gear train is usually designed based on a specification such as rotational speed, direction and torque. A driving rule of the system is given by a motor rating and a particular set of gears. This conventional configuration can be well accepted when the driving rule is fixed. However, for the case where a variable driving rule is desired, it is necessary to have the control system whose function is equivalent to an instantaneous generation of a new set of gear trains. Figure 3 shows an example of a solution to which a mechatronics technology can contribute. Instead of having a physical gear train, each axis is equipped with a motor which can be directly controlled by an electronic control system. The system features a simplified mechanism by eliminating a complex gear train and a higher flexibility in motion control with an electronic control system. The control system employed is a microprocessor based control system where any possible motion control of the mechanism can be programmed by software. This control system is usually named 'Mechatronics Control System' or 'Mechatronics Controller'.

A good example of an application of this multi-axes-independent-control is shown in Fig. 4. The typical mechatronics system shown is a 3-axis orthogonal robot system where a motion in three

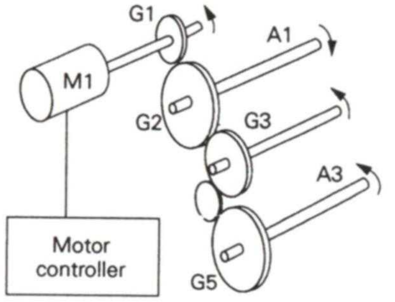

Fig. 2. An example of a conventional system.

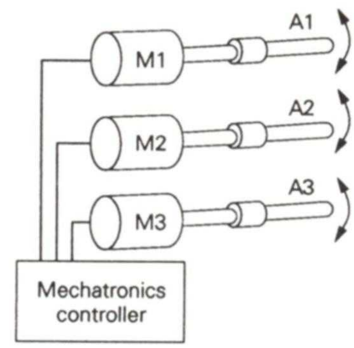

Fig. 3. An example of a mechatronics system.

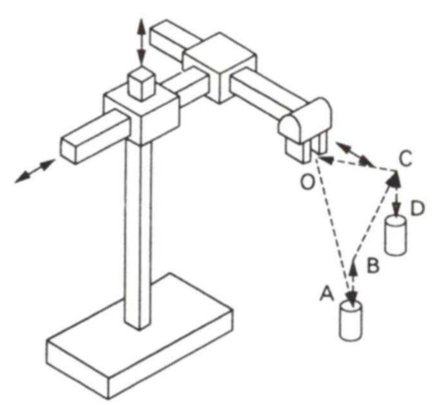

Fig. 4. An example of multi-axes motion control—pick and place control using a robot.

dimensional space with respect to the X-Y-Z coordinate system and grasp/release operation of an end effector can be controlled. In the figure, the control steps for moving an object from point 'A' to point 'D' are also described. As observed in the described steps, a necessary operation of a mechatronics system usually consists of two kinds of control elements 'motion control' and 'sequence control'. A 'motion' is for moving a mechanism with desired acceleration, speed and distance in a space and a 'sequence' is for controlling a discrete event which may take an 'ON/OFF' or '1/0'state.

Figure 5 shows the general hardware configuration of a mechatronics system. The system consists of logic control unit, power electronics circuit, actuator (with sensor), signal conditioning circuit, mechanical system with sensor and man-machine interface unit.

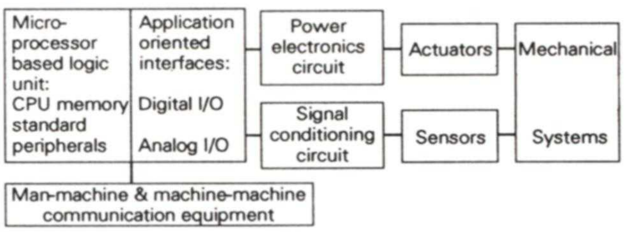

Fig. 5. A general configuration of a mechatronics system hardware.

With these hardware components software should be designed and implemented in the memory of the logic control unit. The application interface in the logic control unit handles input/output signals to and from the power electronics circuit and sensors. In the actual operation, the logic control unit executes custom-designed software for a particular mechanical system control. As a result of the software execution commands to the mechanical system are calculated with respect to the status of the mechanical system and sent to the power electronics system through an information-signal conversion window, application interface. The hardware for CPU basic unit and application interface are a set of electronic components (digital and analog) which are usually arranged in several PCBs (Printed Circuit Boards).

A typical output from the application interface is an electrical signal whose power is very low and is not enough to drive actuators in the system. Actuators may be electric motors such as D.C., A.C. synchronous, A.C. induction and stepping motors or linear ones such as electro-magnetic solenoids. Power electronics circuits should be designed so that an appropriate power to drive an actuator is obtained by using various power adjusting methods such as variable-voltage, variable current and variable frequency. Recent power electronics controls are equipped with large capacity power transistors which can be switched as relatively high frequency resulting in a smooth power adjustment. Furthermore, the software control for switching is available with fast-processing type microelectronics components. The mechatronics control hardware consisting of logic control unit, power electronics circuit, actuator, mechanical system, sensor and signal conditioning circuit is a closed-loop configuration to control a system operation in an automatic fashion. However, a mechatronics system sometimes requires human intervention such as a manual operation of the system. The system also needs to be connected to other mechatronics systems for cooperative automatic operation. A machine tool operated with a robot loading/unloading system is an example of this cooperative operation. In those cases, the control system should have a certain means to communicate with external world and 'man-machine interface' and 'machine-machine interface' need to be provided for this purpose. A man-machine interface usually has keys and switches for input and lamps, segmented LEDs and CRT displays for output. For machine-machine interface, a digital communication based on networking should be employed.

As described above, the major technology components in mechatronics systems are:

(1) Microelectronics Application Technology
Basic Logic Unit and Application Interface
(2) Power Electronics and Actuator Drives
Power Transistor and Electric Servo Motor
(3) Motion Control of Mechanical System
Position, Velocity, Acceleration Control by Software Digital Servo
(4) Discrete Event (ON/OFF) Control of System Operation
Programmable Sequence and Timing Control
(5) Integrated Communication Control for Man-machine and Machine-machine Interface
LAN and WAN networking with standardized protocols and relational database systems.

EDUCATION OF MECHATRONICS CONTROL TECHNOLOGY

Mechatronics being inherently application-oriented, it is important to teach both the latest technology currently available in industries and very basic concepts. As explained in the previous section, the most valuable and sophisticated part of the mechatronics system is a control. Therefore, the mechatronics control should be emphasized when implementing the education. From the functional viewpoint, the digital software servo control and the programmable sequence control are essential. From the academic point of view, on the other hand, a mechatronics control technology is associated with several subjects in the conventional engineering education as shown in Fig. 6. Among

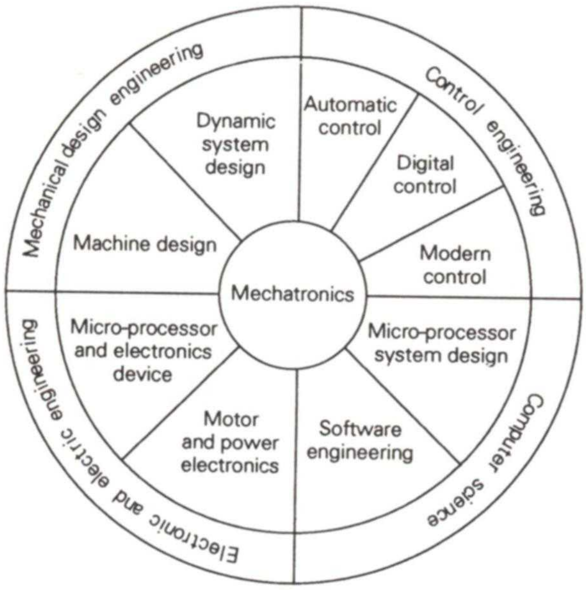

Fig. 6. Principle academic areas associated with mechatronics [1].

these subjects, the upper half of the pie chart of Fig. 6 has been taught in the regular mechanical engineering course in terms of understanding the principle and theory. However, for the mechatronics control education, it is also important to teach how to apply those principles and theory to practical problems. The implementation scheme for mechatronics control systems also requires the knowledge of the lower half of the pie chart of Fig. 6 which has not been well taught in the regular mechanical engineering course. The consideration should be taken such that the education should stress how to apply principles and theory to the practical system by using microelectronics, power electronics and software technologies. One of the most difficult aspects which are hard for students to understand is how to implement the principles and theory of mechanical engineering in the electric and electronics system.

By taking these considerations into account, the course for mechatronics engineering education has been established in 1983 [1]. Although the original course has been designed with lectures and demonstration, it has turned out that the mixture of lecture and hands-on is much better in terms of effective education. Therefore, in 1985, a new course development which includes course arrangements and courseware developments has been implemented. The students to be educated are entering this course at the age of 20 and their backgrounds are mechanical engineering, material science and metallurgy with almost no knowledge of a mechatronics technology. Based on the ability of those students, the course arrangements have been designed as a three steps approach. Table 1 shows the contents of the education to be taught through this approach. The contents have been categorized into total technology, software and hardware, and the three steps are introduction step, specific and detail technology step and practical application step.

Since it was considered that it would be very difficult for students to understand all contents of technologies listed in Table 1 only through lectures, a hands-on teaching method has been introduced in addition to a lecturing method.

MCTS, A NEW TOOL FOR MECHATRONICS CONTROL EDUCATION

For developing an effective hands-on course, a project has been added. The purpose of the project was to develop a set of new hardware and software with which each student can learn the real essence of a mechatronics control technology in the classroom environment. The requirements for the development were as follows:

- The hardware should be as compact as possible so that each student can use it on his own desk in a classroom. The control hardware board should be DIN A4 size which is an equivalent size of a report pad.
- The compact hardware should be provided in the form of 'assemble kit' with which a student can understand the hardware configuration of the mechatronics logic control system by assembling the kit.
- By taking the trends in Application Specific Integrated Circuit (ASIC) technology, a microcontroller (microprocessor with necessary peripherals such as I/O and memory) should be used instead of general purpose CPU.
- The 'Basic' language can be used as well as an 'Assembler' language for software development. Since mechanical engineering students may have little knowledge on an 'assembler', they can start their learning with 'Basic' language to understand the general contents of mechatronics control.
- The 'kit', however, should be designed to be practical and rugged so that an assembled 'kit' and developed software can be used for a particular control application.
- A set of modular control software for education should be prepared so that a student can learn and understand basic operations of the mechatronics system control.

The developed system is named as 'Mechatronics Control Training System' (MCTS)' and the following technologies and knowledge can be learned with this system:

- Concept of microprocessor architecture and its operation
- Application interfacing technology for mechatronics system control
- Concept of software development technology
- Concept of software control technology for mechatronics system.

Table 1. Three steps approach of mechatronics control education

		Software				Hardware				
						Logic Operation Control Unit				
Study Step	Over all Mechatronics Control	Language	Control	Communication	Development Technology	Fundamental Unit	Application Interface	Power Electronics	Actuator	Sensor
Step 1 Introductory Technology	Primitive Technologies Used in Mechatronics Control System.	BASIC and A Little Bit of Assemblers	Digital Software Servo Position Control. Principle of Sequence Control. Simple Realtime Operating System.	Non-Procedural Protocol for RS-232C.	Fundamentals of Editor. Fundamentals of File Management. OFF-LINE Debugging Method.	Principle of Micro-Processor Operation and Memory.	Principle of Analog Input-Output and Digital Input-Output Processing. Principle of Up-Down Counter. Function of Communication. Interface for RS-232C.	Basic Operation of Servo-Amp. Operation Principle of Power Amplification using Power Transistors. Principle of Power Switching.	Operation Principle of Motors (D.C. and A.C.) Operation Principle of Solenoid. Actuator.	Principle and Application Methods of Encoder and Tachometer Generator.
Step 2 Specific and Detailed Technology	Detailed Technologies Based on the Basic Functionality of Mechatronics System.	A Little Bit of BASIC and Assemblers.	Full Digital Software Servo. Practical Sequence Control. Real-time Monitor. Digital Signal Processing.	Fundamental Technologies for LAN. A Protocol for SDLC, HDLC, and Bit-Bus.	Total System Operations of Micro-processor Development System Ranging from Software Generation to Software Debugging.	Architecture and Detailed Operation of Micro-processor and Various Methods of Memory application.	Detailed Mechanism of Analog and Digital Signal Processing Devices and Application Methodology of Them. (Include PAL) Functions of SDLC, HDLC, and Bit-BUS.	Application Methods of Various Types of Transistors Electro-Magnetic Control Technology.	Application Methods of Various Types of Motor and Control Performance.	Details of Current Detection, Overheat Detection, High resolution Encorder, Precision Tachometer Generator and Resolver.
Step 3 Practical Application Technology	Proto-typing Mechatronics Control Systems Using the Knowledge and Technology Studied in Step 1 and 2.	The Same as the above.	Application of the Above Mentioned Technology into Machine Control Application of Modern Control Theory	The Practical Network Protocol for MAP/TOP.	Developmental Environment and Methodology for Custom Design Technology.	Application of DSP and ASIC.	Custom Circuit Design and its Application Hybrid IC, and Gate Array Technology	Application of Smart Power Device	Machine and Actuator Integration Technology	Sensor Technology Using Semi-conductors.

Table 2. Progressive value enhancement of conventional mechatronics systems

System Configuration	Language	Editor	Assemble	Program Execution	Program Debug	File Management	Appropriate Study Step
MCTS + (Key Board & Display)	BASIC & Assembler	Line Editor in MCTS	Using an on-Board Assembler in MCTS Advanced Training Bench.	BASIC Program & Machine Language Program Execution.	Using an on-Board Debugger in MCTS Advanced Training Bench.	Using a PROM Writer on MCTS.	Step 1 & Parts of Step 2.
MCTS + Personal Computer	The Same as the above.	Line Editor in MCTS & Screen Editor in Personal Computer.	Using an on-Board Assembler in MCTS & 8052 Assembler System with a Personal Computer.	The Same as the above.	The Same as the above.	Using a PROM Writer on MCTS & External Memory Device (FD, HD) in a Personal Computer.	Step 1 & Step 2.
MCTS + Microprocessor Development System	The Same as the above	Line Editor in MCTS & Screen Editor in Microprocessor Development System.	Using an on-Board Assembler in MCTS & 8052 Assembler System with a Micro-processor Development System.	The Same as the above.	Using an on-Board Debugger in MCTS & In-Circuit Emulator with a Microprocessor Development System.	Using a PROM Writer on MCTS & External Memory Device (FD, HD) in a Micro-processor Development System.	Step 1 & Step 2 & Step 3.

The MCTS has been designed so that three kinds of hardware configurations are available in accordance with the education level and peripheral hardware resources available. These three kinds of set ups have differences in the utilization capability for software development as shown in Table 2. The term 'advanced training bench' represents a small one board PCB hardware to be connected MCTS when assembler and debugger environment is required.

Table 3 shows the hardware specification of MCTS. Intel's 8052 microcontroller chip with resident on-chip FA-BASIC interpreter has been adopted as a main CPU. This special chip has originally been developed by Intel Corporation and marketed as 'MCS BASIC-52' chip. The chip integrated the 8051 CPU core, 8K-byte on-chip memory (for resident BASIC interpreter), I/O controller, serial communication controller, etc. With the serial communication controller, the chip is easily connected to the external terminal (i.e. alpha-numeric key board and CRT display) via the RS-232C standard driver and receiver and very compact BASIC system can be realized with the least chip-count hardware. Since most personal computer systems have the RS-232C port and can be operated in the 'terminal mode', the MCTS can be hooked up to the personal computer system for man-machine interfacing.

The assembled MCTS is shown in Fig. 7. Since the PCB and selected parts used in MCTS meet the industrial standard in terms of reliability and

Table 3. A functional specification of MCTS

	Item	Functional specification
1	Size	DIN A4, On-Board Microprocessor Based System
2	Memory (excluding on-chip ROM)	Data Memory (32KB) Program Memory (Object Code) (Up to 16KB)
3	Language	FA BASIC Interpreter
4	Operation	Full Duplex Serial I/O with External Terminal (CRT,KBD) via RS-232C Communication Interface
5	ROM Programming	Equipped with On-Board PROM Writer. Possible to Write Developed Source Program to PROM (2764, 27128)
6	A/D Conversion	8 Bits A/D Converter, 3 Input Channels
7	D/A Conversion	8 Bits D/A Converter, 3 Output Channels
8	Encoder Input	8 Bits Up-Down Counter, 3 Input Channels
9	Relay Driver Output	On-Board Lead Relay Output 4 Channels Capacity: 20VA
10	Digital Input	4 Channels Photo-Isolated Input
11	Digital I/O	TTL Compatible 16 Bits (8 Bits*2 Channels)I/O
12	Pulse Width Modulation	1 Channel PWM Output

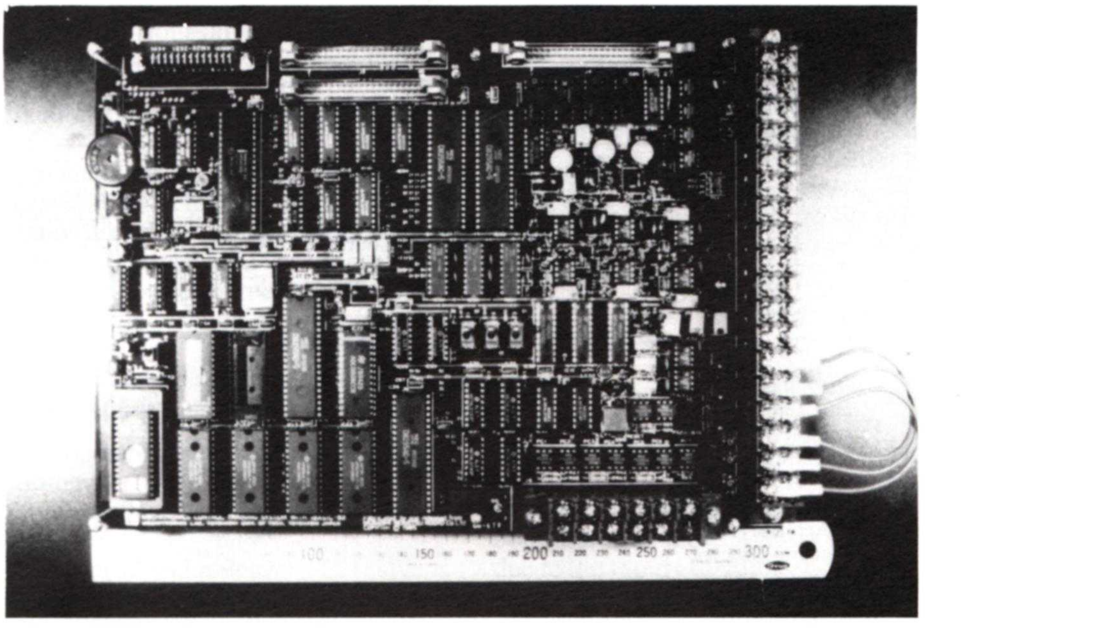

Fig. 7. Assembled MCTS board.

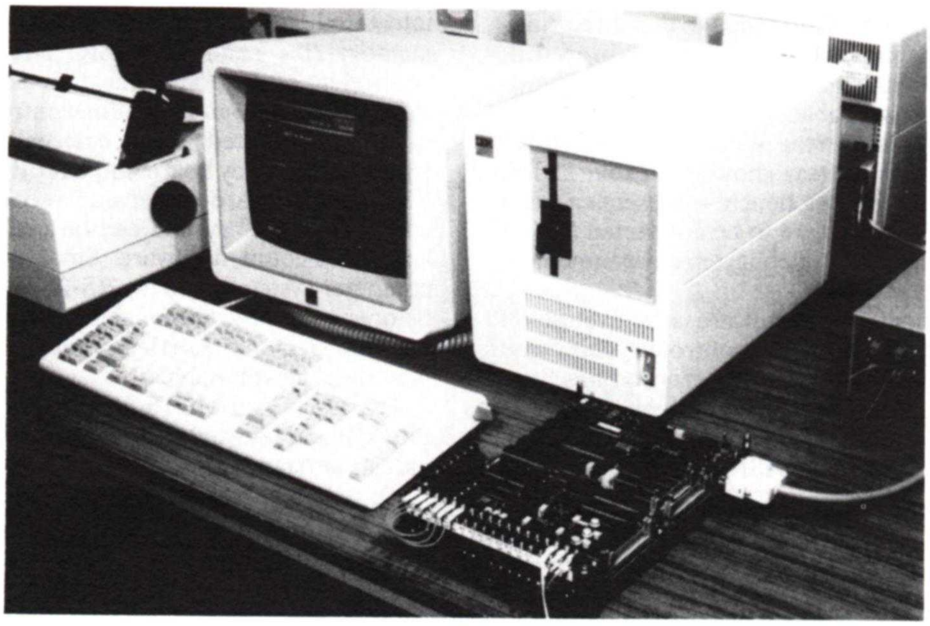

Fig. 8. Typical training station of MCTS.

durability, MCTS can be used as practical controller in a real industry environment after training is completed.

The typical training station is shown in Fig. 8. MCTS can be hooked up to any type of personal computer system having RS-232C serial communication port with a single cable. Only a key board and a CRT display of the personal computer system are normally used during training and MCTS CPU with the training system software in ROM (Read Only Memory) performs necessary interactive operations by a trainee.

A set of structured training software has also been developed as shown in Fig. 9.

AN EXAMPLE OF IMPLEMENTATION OF THE DEVELOPED COURSEWARE

The developed courseware has been implemented in the university and 20 classroom hours (10 hours of lecture 10 hours of hands-on) education has been implemented. To evaluate the effectiveness of the developed course the same tests have been performed before and after the course without any notice. Table 4 shows the results of the evaluation.

CONCLUSIONS

Based on the experience of organizing the educational activities for 'Mechatronics Engineer-

Table 4. Topics of questions and correct answer statistics

Topics of Questions	Distribution of Points	Right Answer (Before the Course) A	Right Answer (After the Course) B	Learning Effect B/A
The Overall Mechatronics Control	30 points	73/8%	89.1%	1.21
Logical Operation Fundamental Unit	20 points	43.0%	89.3%	2.08
Logical Operation Application Unit	10 points	6.1%	67.2%	11.02
Fundamental characteristic of Actuator	30 points	53.7%	70.7%	1.32
Numeral Concept for Mechatronics Control	12 points	38.2%	75.8%	1.98
Total	102 points	50.4%	79.9%	1.59

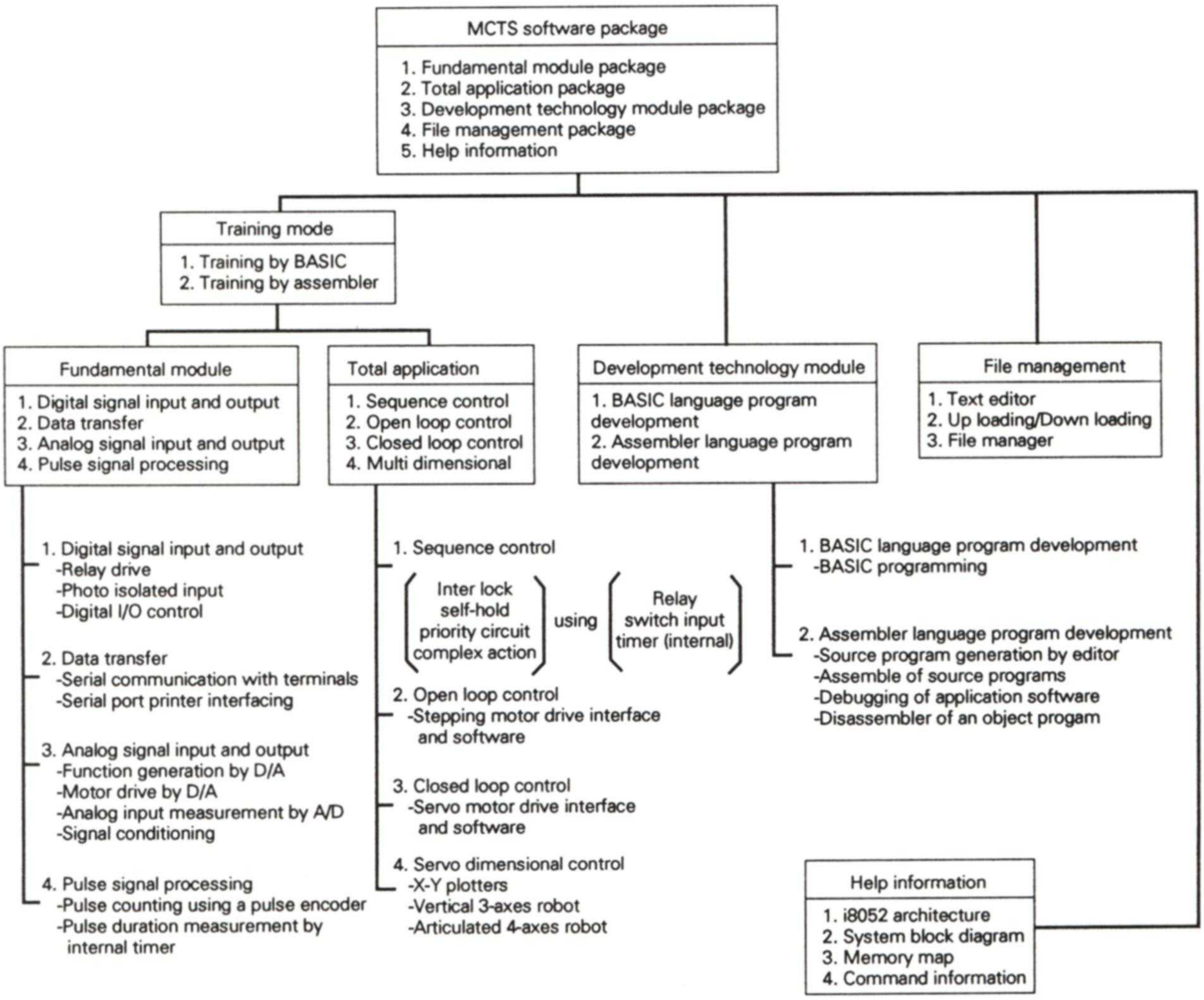

Fig. 9. A structure of training software for MCTS.

ing Education at Toyohashi University of Technology', the following conclusions can be made:

(1) The concept of the mechatronics control technology should be identified as a complex set of technologies such as mechanisms, electric and electronics hardware and software.
(2) In order to maintain a continuous growth of mechanical system technologies, the educational system for mechatronics engineering should be well organized such that a mechanical engineer can freely handle the complex set of the technologies mentioned in (1).
(3) The following 5 technologies are the keys for mechatronics control:
   - Microprocessor hardware application technology
   - Power electronics and actuator control technology
   - Motion control technology
   - Discrete event control technology
   - Integrated data communication technology
(4) For effective training, a hands-on approach closely tied up with an ordinary lecture has been organized.
(5) The technological items for mechatronics control education have been identified and classified in relation to a 3-steps approach.
(6) A set of courseware has been developed aiming at the effective training for mechanical engineering students. The developed courseware consists of the compact mechatronics control training system (MCTS) hardware and structured training software for the classroom-environment hands-on training.

One of the most difficult parts of the mechatronics control technology is to justify an optimum assignment of total required functions of a particular mechatronics system to 'Mechanism', 'Electric and Electronics Hardware' and 'Software', because the boundaries of these 3 areas are always changing due to the rapid growth of electronics and software technology which is still advancing today.

The future shape of the mechatronics control technology will be more integrated technology

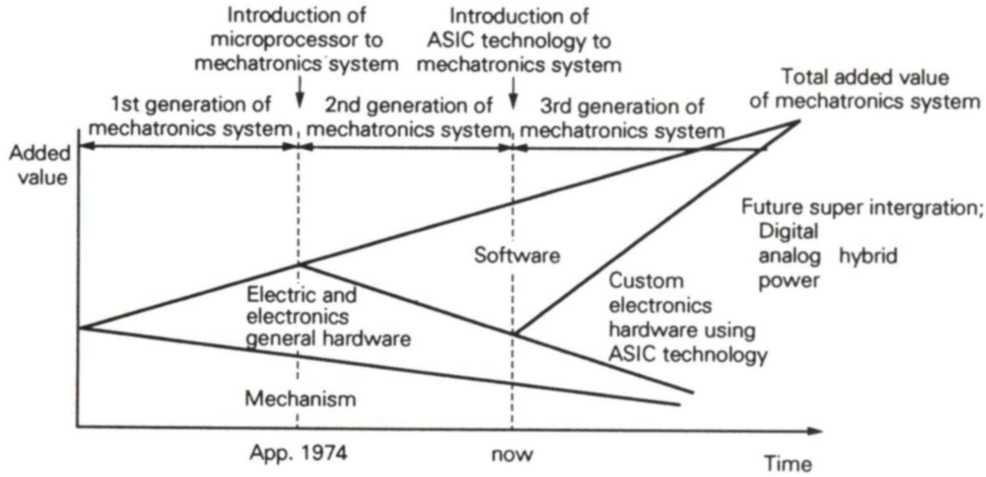

Fig. 10. Progressive value enhancement of the super mechatronics system assisted by ASIC technology.

where a discrimination of the hardware and software will become hard and ASIC (Application Specific Integrated Circuit) and Silicon compiler technologies will allow mechanical engineers to design and fabricate their own custom IC instead of currently popular PCB (Printed Circuit Board) based technology including analog and power electronics circuits as well as digital circuit. (Fig. 10).

Since the mechatronics control technology is application oriented technology, the comprehensive education should simultaneously be emphasized on both the primitive concept and the advanced element of related technologies.

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