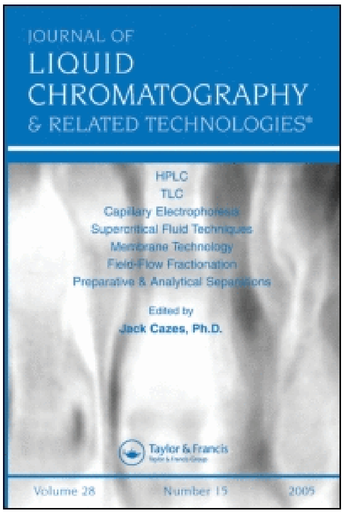

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The Anatomy and Function of the Laboratory Robot

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THE ANATOMY AND FUNCTION OF THE LABORATORY ROBOT

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ABSTRACT

The design and operation of a typical user-programmed laboratory robot system is discussed. A laboratory robot is defined as a integrated system of robot arm, controller and laboratory peripherals. The capabilities together with limitations of the current generation of robots and the design specifics of two typical laboratory robot systems, the Zymate and the Perkin-Elmer Masterlab, are presented.

INTRODUCTION

The use of robots in the manufacturing sector is well established and much of the technology currently used in laboratory robotics is derived from industrial robots. Industrial engineers find that the use of robots on the assembly line leads to a reduction of product defects, savings in manufacturing cost and a decrease in the re-tooling time required to bring a new product to the market (1). Similarly, analytical chemists highlight greater precision, higher throughput (2) and the possibility of "soft-automation" as the principal

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advantages of laboratory robotics (3). It is due to these advantages that an increasing number of robots are being installed in laboratories and the number of suppliers of laboratory robots is growing. Currently, there are approximately fifteen different suppliers of robotic equipment in the U.S. analytical instrumentation market. Among these are: Zymark Corp., Perkin-Elmer Corp., Hewlett Packard Corp., John Scale Co., Beckman Instruments, Radian Corp. and GCA Corp. Even greater competition in the laboratory robot market is undoubtedly on the horizon.

Before committing oneself to a particular line of robotic equipment, one must identify a robot system that is capable of performing the type of chemical analysis required. Significant differences exist between a well-designed laboratory system and an "assembly-line" robot of the type commonly used in the electronics industry; although some robots in Computer Aided Manufacturing (CAM) (4) are as sophisticated, and often much *more* sophisticated, than the current generation of laboratory robots.

Robots can be classified, according to their end-use, into several categories: educational/personal robot (see Figure 1: The Hero 2000 robot), hydraulic assembly robot (e.g. the Cincinnati Milacron T3 robot used in automobile assembly plants), electrical and pneumatic robots used for light assembly work (Figure 2) and military/security robots (e.g. a bomb disposal robot (5)).

Even though a typical laboratory robot resembles an electrical assembly robot in many of its mechanical specifications, laboratory robots already installed in the academic and industrial laboratory are different from "pick-and-place"assembly robots and should be classified into a separate category.

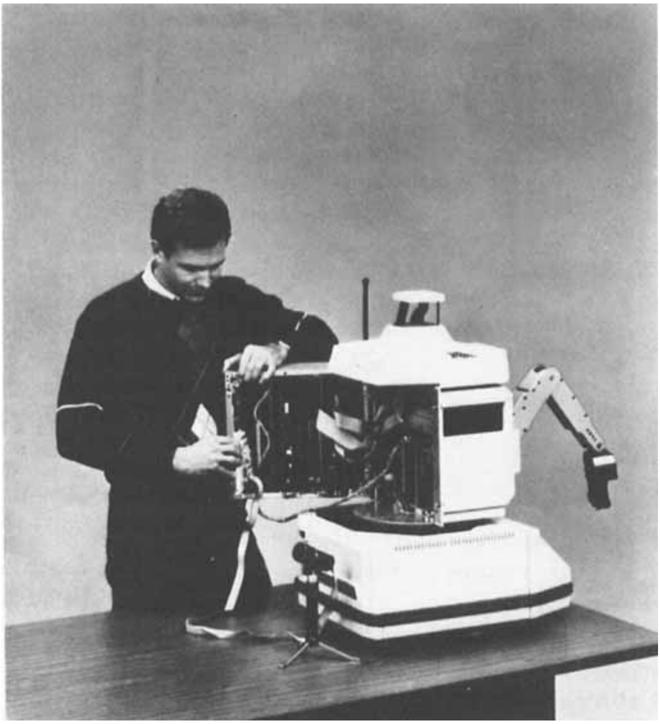


Figure 1. The Hero-2000 Educational robot, part of a Heathkit educational system, is designed to teach students and industrial workers concepts in robotics and automation. The Hero-2000 is shaped like the popular RD2D2 in the motion picture Star Wars.

The Robot Institute of American defines a robot as "A reprogrammable multi-functional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions. . ." and therefore regards the robot as a programmable mechanical arm with tools attached.

While an assembly line typically consists of tens of robots and the task performed by an individual robot is relatively simple, a laboratory robot system usually consists of only a single robot arm.

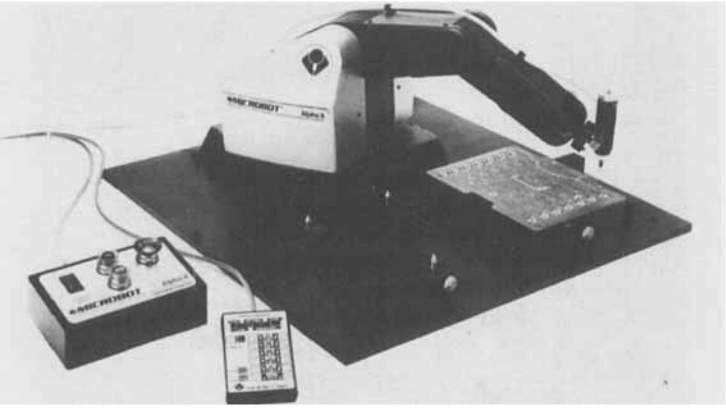


Figure 2. The Microbot Alpha-II, a typical "one-arm bandit" type robot found in many laboratories and assembly plants. The Alpha-II is shown working with an electronic circuit board.

This laboratory system must perform a complex sequence of manipulations involving sophisticated laboratory instruments and apparatus and in some applications, be able to make intelligent decisions and generate reports during the course of an experiment (6). With this perspective, a laboratory robot is perhaps more accurately described as "An integrated system consisting of an electro-mechanical manipulator arm and instrument interface capable of interacting with a typical laboratory environment".

What Is a Laboratory Robot?

The current generation of working laboratory robots usually have the following components. Details of these components will be further discussed.

1) An electrically (DC-Servo motor) driven robot arm with interchangeable hands or "end-effector" functions.

2) A microcomputer "controller" with its own, high-level, robotics oriented and easy-to-use language. (For example: the Zymark Corp. EASYLAB and the Perkin-Elmer Corp. PERL robotic languages). This microcomputer is analogous to the part of the human brian that control human motor functioning. Without this "motor function" controlling computer, the robot-arm must be programmed explicitly - e.g.-in assembly and is very difficult to train.

3) A set of laboratory peripherals, such as weighing station, a vortex mixer, pipetting station, sample racks and a "power-and-event" controller. The "power-and-event" controller is capable of actuating switches, converting analog signals to digital form, supplying AC and DC power and acting as an interface between the robot controller and the various laboratory instruments.

4) A computer interface that allows the controller to communicate with an external computer. The robot controller is usually fully occupied with controlling the motor functions of the robot system. Any other computational or information-storage/retrieval tasks must usually be performed with an external computer such as a laboratory management computer (LIMS), a low-cost computation oriented microcomputer or an artificial intelligence-based computer system.

The Robot Arm Configuration

Currently, there are at least four types of robot arm configurations (cylinderical, revolute, cartesian and SCARA) being marketed by diffirent laboratory instrument suppliers. The cylinderical configuration (7), - i.e. - the Zymate, is currently the most widely implemented laboratory robot configuration (see Figure 3a).

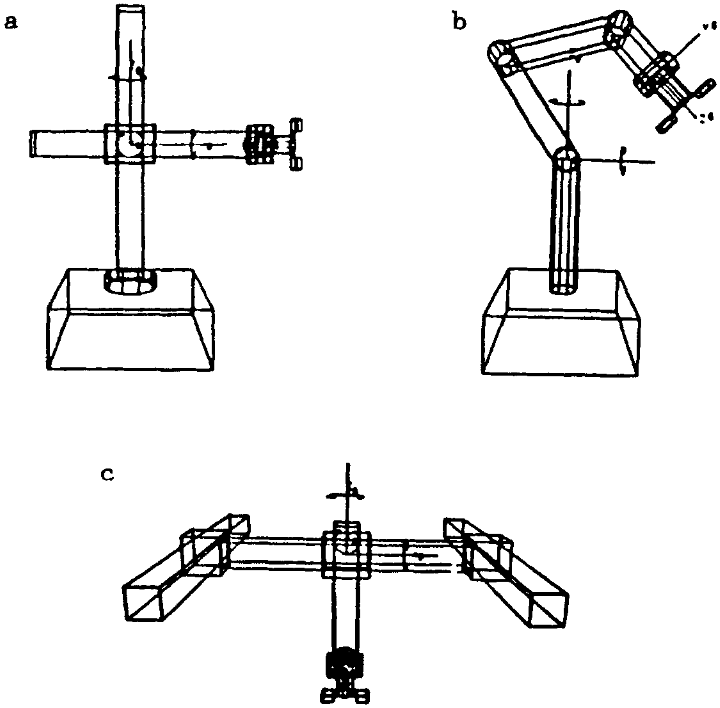


Figure 3. a) Schematic representation of a cylindrical coordinate robot arm configuration. b) Schematic representation of a revolute robot arm. c) Schematic representation of a cartesian coordinate robot.

The Mitsubishi Movemaster robot uses a revolute (see Figure 3b) coordinate system (7) and is perhaps the most dexterous laboratory robot arm available. The Mitsubishi Movemaster is marketed by the Perkin-Elmer Corporation as part of the P.E.-Masterlab robot system (see Figure 4). The same robot is also sold by Johnson Scale Co. as the JOSCO Smart Arm robot (see Figure 5)

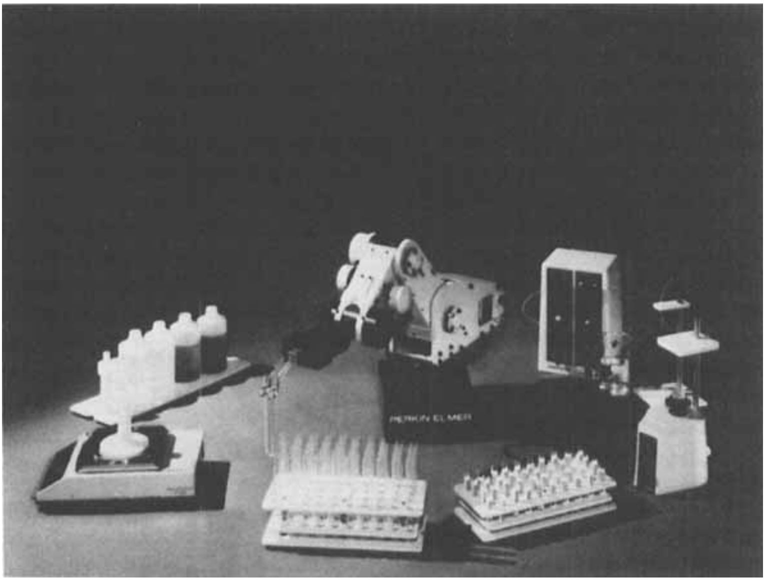


Figure 4. The Perkin-Elmer Masterlab robot system.

Radian Corporation used the IBM-75665 cartesian robot (see Figure 3c) as well as the IBM-7547 SCARA robot in their laboratory robot systems. The IBM cartesian robot is certainly as dexterous as a typical revolute robot but is significantly larger and more expensive. The Radian/IBM-7565 cartesian robot is primarily designed for the high-throughput and "factory-programmed" systems and will not be covered in this review.

The SCARA robots uses a unique double cylindrical coordinate and is shown in Figure 6.

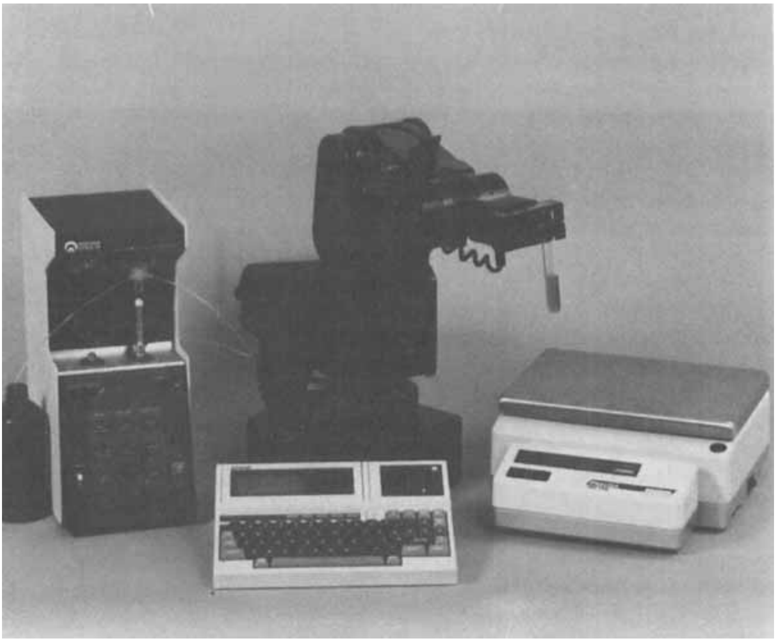


Figure 5. The JOSCO-SMARTARM™ robot shown with an Epson HX-40 computer, a digital balance and a digital pipet.

Wrist rotation in a SCARA configuration is not possible since the hand of a SCARA robot always faces down. The SCARA type robots (the IBM-7547) and the GCA/DKP300H are designed to work with low profile surfaces such as electronic circuit boards or ELISA microplates. The SCARA robots have been used for limited "pick-and-place" tasks in the laboratory environment as well.

The Zymate Robot Arm

The Zymate's cylindrical coordinate robot arm is designed for sample preparation. Multiple-sample tube-rack operations typically involves horizontal motions.

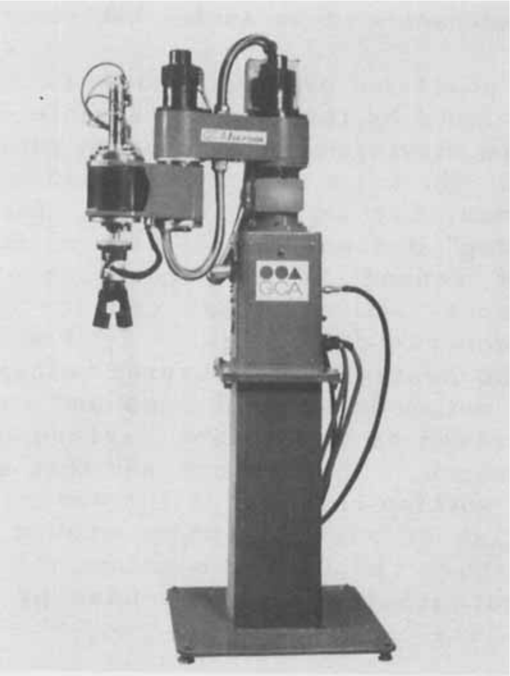


Figure 6. The CGA/DKP300H pneumatic SCARA robot.

For example, a typical multi-sample rack operation is a movement from rack position 1 to position 2. Such as horizontal motions can be easily handled by a simple rotation of the robot base and an extension of the robot arm. The same maneuver by a revolute robot will require the movement of a larger number of joints and therefore a revolute robot generally requires a more sophisticated control system. The Zymate has a reach of 60 cm, elevation of 56 cm, a load capacity of 2 kilograms and a positioning accuracy of + 2.5 mm. The robot can rotate 370 degrees around its base and 360 degrees around its wrist. The Zymate uses a "closed-loop" (8), DC-servo motor, cable-driven design which is very similar to the drive mechanism of an analog X-Y recorder.

Each position of the robot arm in space is uniquely defined by three separate cable drives which control the elevation, extension and rotation of the robot arm. The wrist rotation is also controlled by a servo-motor but is gear driven. In the Zymate "closed-loop" design, the position of each of these drives is sensed by a potentiometer and the potentiometer voltage is compared with the computer-generated voltage. If the difference between the desired and measured voltages is zero, the servo motor drive will stop and the robot arm will be driven to a position defined by the four servo-voltages. Thus we can see that any position within the working envelope of the arm can be defined by the value of servo-voltages stored in memory. Figure 7 shows the DC servo motor, the cable drive and the potentiometer at the base of the Zymate robot.

The most unique feature of the Zymate robot is its interchangeable hands (see Figure 8) which use a patented self-locking mechanism.

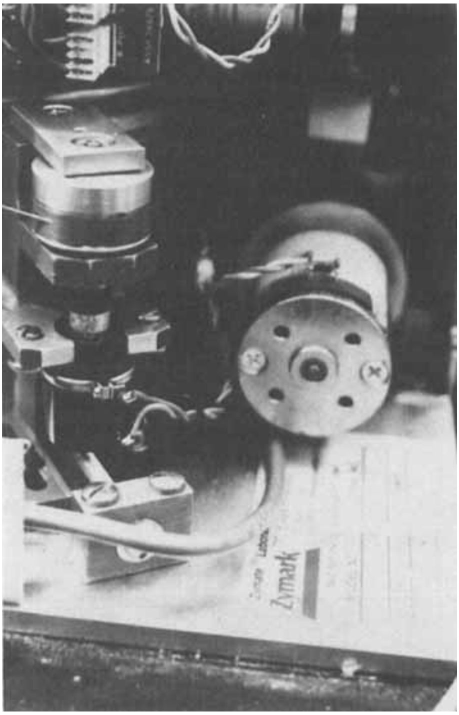


Figure 7. The drive and feed-back mechanism at the base of the Zymate robot. The upper scale transmits power from the servo-motor and the lower (thinner) cable drives a potentiometer which provides a feed-back voltage for the Zymate controller.

This versatility has proved to be very important in real life applications of laboratory robotics.

The Perkin-Elmer Masterlab Robot Arm

The Masterlab robot uses a revolute coordinate with five degrees of freedom (See Figure 9).

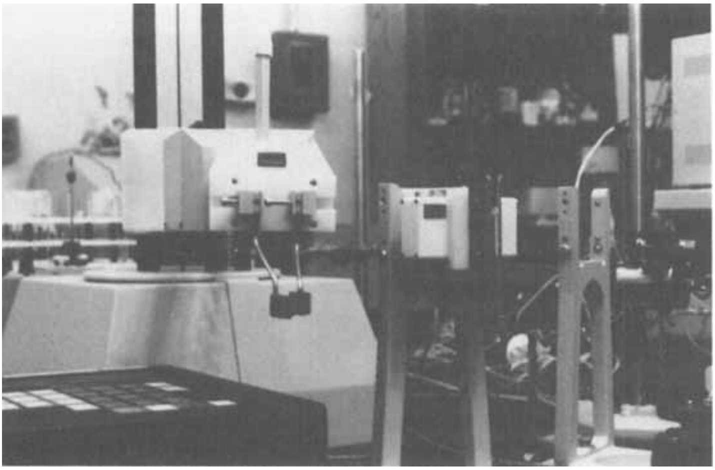


Figure 8. The Zymate system equipped with interchangeable hands. A standard gripper-hand and a syringe-hand are shown.

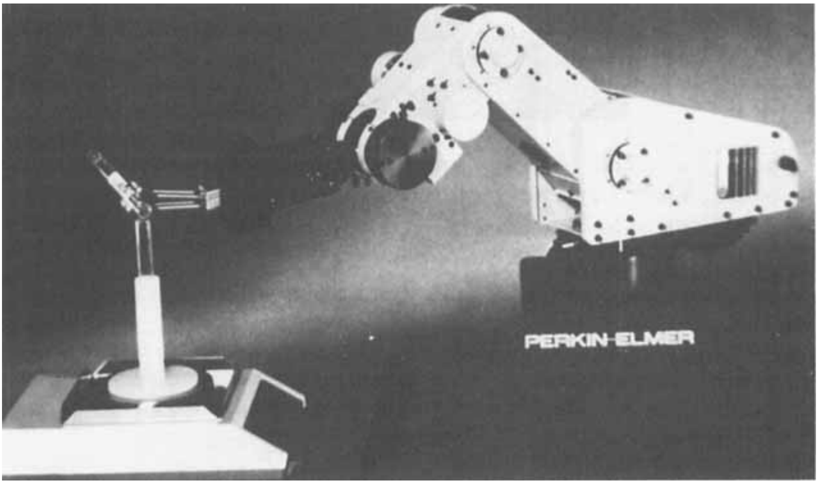


Figure 9. The Perkin-Elmer Masterlab Robot shown in the process of performing a "bend-wrist" operation.

It can rotate 300 degrees around the base, 130 degrees at the shoulder, 90 degrees at the elbow plus a 90 degree wrist-pitch and an 180 degree wrist-roll. The maximum speed of the robot is 400 mm/sec (15.75 in/sec) programmable in 10 steps. The robot is also driven by DC-servo motors under "close-loop" control and has comparable speed and load capacity (1.2 Kg) as the Zymate. Instead of using cables and potentiometers, the MasterLab robot uses gear drives and optical position encoders (8) resulting in a higher positioning accuracy of + 0.5 mm. The robot could be mounted on a rail thus increasing the size of its operation envelope (see Figure 10).

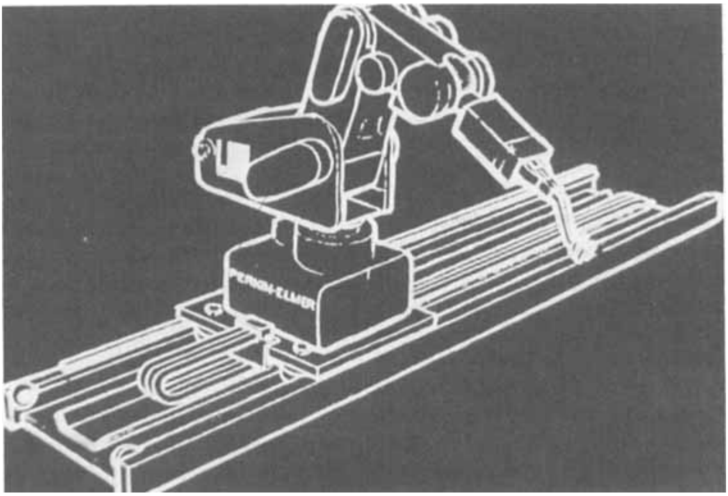


Figure 10. Schematic diagram of the P.E. Masterlab robot mounted on a rail.

The Masterlab robot is a much more human-like robot and is capable of performing manipulations that the Zymate is not capable of. For example, it can retrieve centrifuge tubes from a typical slant-tube rotor, perform smooth pouring motions and insert needles to a horizontal G.C. injection-port. With suitable system enhancements, the Masterlab can, in principle, perform complete chemical analysis that is normally performed by technicians.

The Masterlab has a variety of interchangeable hands but the hands cannot as yet be interchanged under program control. The inability to change hands under program control, without human intervention, is often perceived as one of the current drawbacks of the Masterlab system. Hands that can be interchanged under program control will be offered with the Masterlab system in the future.

Control of the Robot

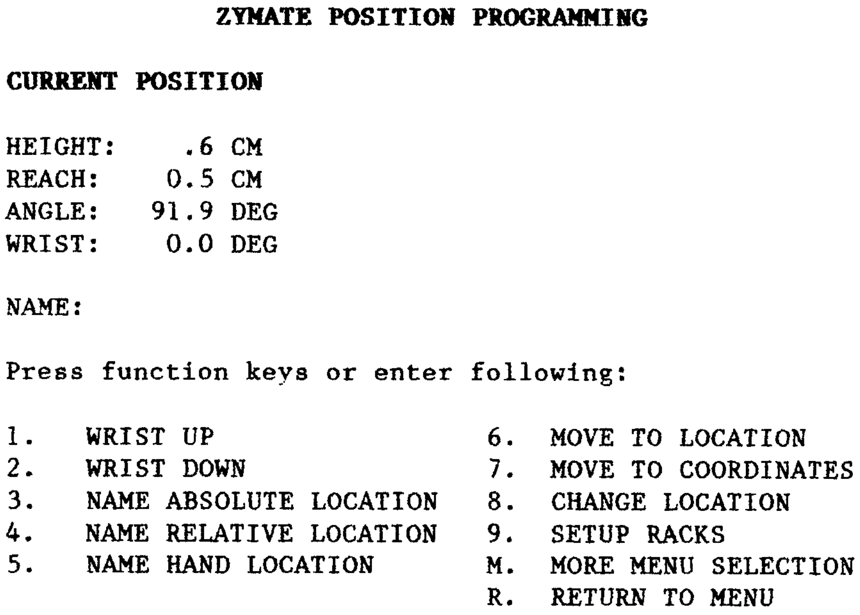
Typically, a laboratory robot is programmed in a "point-to-point mode, while some industrial robots can be programmed in a "continuous-path" mode. The continuous-path control method generally requires a mini-computer and a large amount of memory and is therefore not used in the current generation of laboratory robots. In the "continuous-path" mode, the robot can be led through a sequence of operations by a human operator and at the same time a "teaching" program records the time-dependent position of the robot arm periodically (for example, every 1/10 sec). Once the teaching process is completed, the robot can then "play-back" the recorded positions from its computer memory. This type of control is necessary for procedures such as spray-painting or arc-welding. In these processes, there is a need to control the exact path taken by the robot as well as the amount of time spent at each spatial coordinate.

In contrast, laboratory robots are typically controlled in a "point-to-point" mode which involves the simultaneous movement of all axes of the robot arm. The hand (or tools) attached to the end of the robot arm is moved from point A to point B along the shortest possible path. Often a robot programmer must break down the large sweeping motions of the robot into smaller segments in order to avoid collision with objects around the robot arm. In fact, one of the first tricks that a laboratory robot programmer must learn is to raise and retract the arm to a safe level before any long, sweeping rotation of the robot arm is executed. Otherwise, the robot can sweep everything off the laboratory bench while it tries to swing its robot arm from one side of the bench to the other! The position "INJECTION.VALVE.CLEAR" shown in Figure 12 is such a collision-avoidance position.

Control of the Zymate

The Zymate is controlled by a custom-designed 16-bit microcomputer (Intel 8088 type CPU). The Zymate controller has a 5 1/4 inch flexible disk-drive, non-volatile memory (battery operated CMOS RAM), a device-interface board, a set of programmable function keys and a menu-driven robotics language (EASYLAB) stored in read-only memory (ROM). Normal operation of the Zymate rarely requires disk read-write operations.

A typical programming sequence in EASYLAB usually begins with the "Bench and Module Setup" menu shown in Figure 11. The "UP", "DOWN", "IN", "OUT", "CLOCKWISE" and "COUNTER-CLOCKWISE" teaching function keys position the robot arm in a cylindrical coordinate. The wrist and the hand are controlled by the "1"/"2" and "OPEN"/"CLOSE" keys.



```
                ZYMATE POSITION PROGRAMMING

CURRENT POSITION

HEIGHT:     .6 CM
REACH:     0.5 CM
ANGLE:    91.9 DEG
WRIST:     0.0 DEG

NAME:

Press function keys or enter following:

1.   WRIST UP                     6.   MOVE TO LOCATION
2.   WRIST DOWN                   7.   MOVE TO COORDINATES
3.   NAME ABSOLUTE LOCATION       8.   CHANGE LOCATION
4.   NAME RELATIVE LOCATION       9.   SETUP RACKS
5.   NAME HAND LOCATION           M.   MORE MENU SELECTION
                                  R.   RETURN TO MENU
```

Figure 11. The "Bench and Module Setup" menu for the Zymate robot arm. This position programming utility in EASYLAB allows the robot programmer to define and name any spatial coordinate within the reach of the robot arm.

By the use of these function keys, the programmer can instruct the robot arm to move to any point within its operating envelope. Once the desired position is reached, the position of reach of the robot "joints" is sensed by a potentiometer (see Figure 7 shown previously), converted into reach, height and degrees rotation and displayed on the screen. By using the "NAME ABSOLUTE LOCATION" option in the menu, the potentiometer voltages and hence the position of the robot arm can be stored in memory. For example, positions that needs to be defined for an HPLC injection sequence are OVER.INJECTION.VALVE, ON.INJECTION.VALVE and INSERT.INJECTION.VALVE shown in the sample program HPLC.INJECT (see Figure 12). The MOVE TO COORDINATES option on the menu allows explicit programming of the robot arm in terms of absolute height, reach and angle but it is usually more convenient to use the teaching function keys.

EASYLAB PROGRAM: HPLC.INJECT

```
injection.valve.load.position
injection.valve.clear
over.injection.valve
on.injection.valve
insert.injection.valve
hand.10
injection.valve.inject.position
nelson.start.on
over.injection.valve
injection.valve.clear
nelson.start.off
hand.0
injection.valve.load.position
```

Figure 12. EASYLAB program HPLC.INJECT illustrating the control of the injection valve.

Once all the necessary positions for a coordinated sequence of movement is defined, the positions can be chained together to create motion in a "point-to-point" mode. The EASYLAB software is organized like FORTH and a sample program for a complete HPLC analysis is shown in Figure 13. Each line of the program TERNARY.HPLC represents a complete sequence of positions. For example, calling the line HPLC.INJECT shown in Figure 12.

EASYLAB PROGRAM: TERNARY.HPLC

```
attach.gripper.hand
finger.down
over.key.pad
calculate.solvent.composition
program.key.pad
equilibrate.column
finger.up
park.gripper.hand
hplc.inject
```

Figure 13. EASYLAB program TERNARY.HPLC.

Control of the Perkin-Elmer Masterlab Robot

The Masterlab system is controlled by an IBM-PC (see Figure 14) equipped with the Perkin-Elmer Robotics Language (PERL) which is a menu-driven, user-friendly language like EASYLAB (see Figure 15).

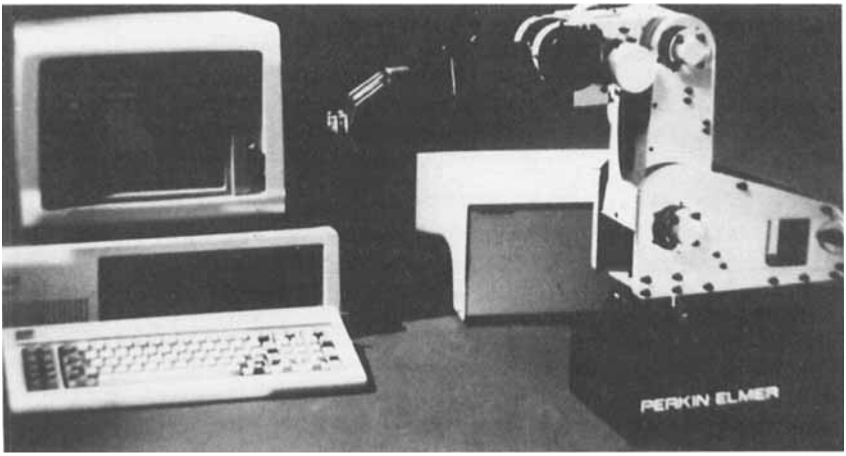


Figure 14. Photograph of the P.E. Masterlab robot shown with is controller, an IBM-PC.

Similar to the Zymate, it is programmed in a point-to-point ;mode. A typical teaching sequence begins with the definition of positions using a teaching pendant(see Figure 16).

PERL PROCEDURE: move to mixer

```
above mixer
down 5 cm
open-gripper
up 2 cm
turn on mixer
set timer 1 for 15 seconds
wait for timer 1
turn off mixer
down 2 cm
close gripper
above mixer
```

Figure 15. A sample Perkin-Elmer Robotics language (PERL) program.

Once the desired position is reached, it can be named and stored in the IBM-PC and used in subsequent programming. PERL has built-in rack-positioning utilities and the programming method is very similar to the Zymark EASYLAB language. The only noticeable difference is that the standard IBM-PC has volatile memory and therefore the coordinates of the robot positions must be read from a disk during start-up. Given the current advances in Winchester disk technology, this may be a more secure way of storing programs and robot positions than the method used by the Zymark controller (CMOS RAM and Floppy disk).

System Integration

The extent of the ability of the robot to interact with instruments and laboratory peripherals can determine the success or failure of a robot system.

Figure 16. The teaching pendant for the P.E. Masterlab robot.

Although the current generation of laboratory robots lacks the tactile and video sensors often found in some advanced CAM robot systems, Perkin-Elmer and Zymark have achieved a remarkable degree of system integration in their robot systems. A well integrated robot system is able to work with instruments external to the robot system and this capability is made possible by a number of well designed accessories within the robot system.

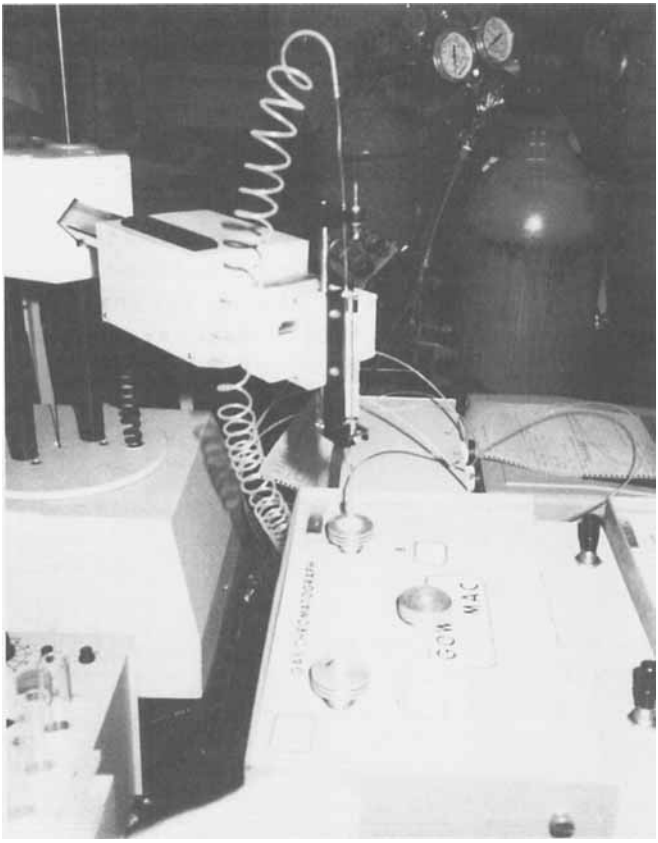


Figure 17. A Zymate robot injecting sample into a GOW-MAC gas chromatograph.

In our laboratory, we have successfully interfaced the Zymate with several Apple computers

(9), an IBM ternary-phase HPLC, an HP-5880A gas chromatography (10), a Nelson Analytical chromatographic data-station, a GOW-MAC 550 GC (see Figure 17) and a rather robot-unfriendly Bausch & Lomb Spec-20 spectrometer (11). Perkin-Elmer has demonstrated that the Masterlab system can be interfaced to a modern UV-VIS spectrophotometer, a differential scanning calorimeter, an ICP emission spectrometer, automatic titrators and a number of gas and liquid chromatographs.

System Integration in the Zymate

Besides the robot arm, the Zymate controller typically controls an electronic balance, a Masterlab Station (syringe system) and a vortex mixer in a typical Zymate system. This basic system will allow the Zymate to perform most of the routine sample preparation chores.

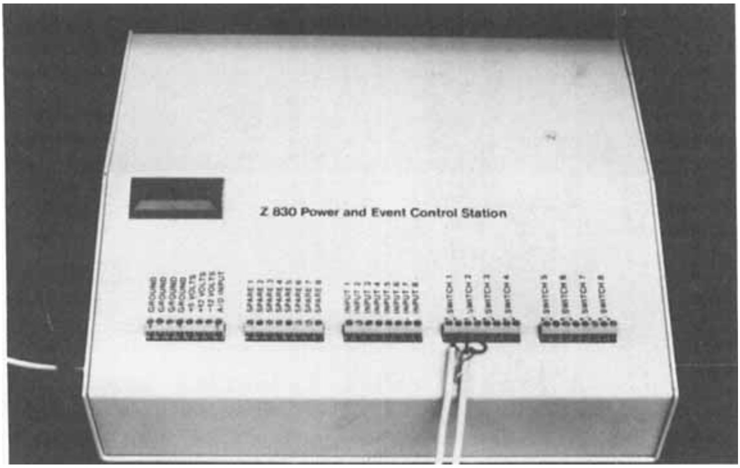


Figure 18. The Zymate Power-and-Event Controller.

In a more advanced system, the Power and Event Controller (PEC), shown in Figure 18, is an especially note worthy feature. Like all of the accessories in the Zymate system, the PEC can be directly controlled by the menu driven EASYLAB software and provides a direct interface with the apparatus in the laboratory. The PEC consist of eight programmable on/off switches, eight on/off sensors, two programmable AC power outlets, one variable AC power outlet, one 0 to 2 Volts ADC (analog-to-digital converter with 1 mV resolution), an optional preamplifier for the ADC and a DC power outlet at + 5V and +12V.

Zymark Corporation was the first company to supply user-trained laboratory robots and has created a new market that had not existed previously. Since the sale of its first robot in 1983, the experience with working directly with the customer has led Zymark to offer an array of very useful accessories for the Zymate system. For example, Zymark now offers an HPLC injector station, automatic buret and titrator interface, two sample-vial capping stations, fraction collector, sample tube dispenser, automatic door opener for the electronic balance (to reduce air turbulence) and specially designed instrument interface for Hewlett Packard laboratory equipment (GC, HPLC and UV/VIS). Zymark also offers the CONFIRM™ devices which are microswitches to verify the attachment of pipet tips and sample tubes to the robot hands. Custom engineering is also available.

System Integration in the PE Masterlab

The Perkin-Elmer Movemaster robot utilizes the popular and versatile IBM-PC as its controller. The IBM-PC, with suitable enhancement, can be converted into a very powerful computer and Masterlab system appears to have taken advantage of this. As a result, the Masterlab system can use directly a large number of laboratory control and measurement devices already adapted to be used with this industry standard computer.

The Perkin-Elmer approach to robotics has been one of system integration and, therefore, differs from Zymark in a number of ways.

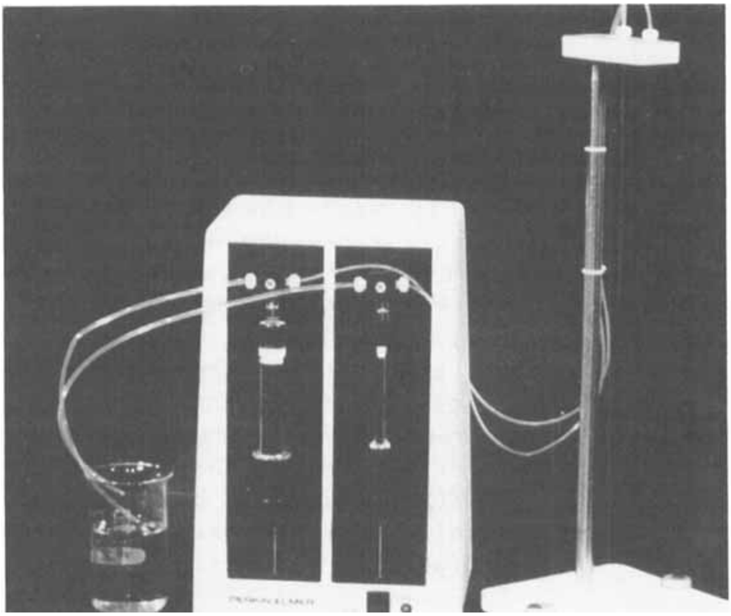


Figure 19. The Perkin-Elmer "MasterSyringe" pipeting system. This syringe system is controlled by an RS-232 interface and has a higher volumetric accuracy than the Zymate Masterlab Station syringe system.

Instead of using a custom-design interface board for each peripheral device, the Masterlab system uses a standard RS-232C asynchronous interface to control most of the peripherals in the system. A basic Masterlab system consists of an IBM-PC (256K, dual floppy drives), the robot arm, the teaching pendant (Figure 16), a high-precision syringe station (Figure 19), a electronic balance station (Figure 20) and a multi-port asynchronous interface (Figure 21).

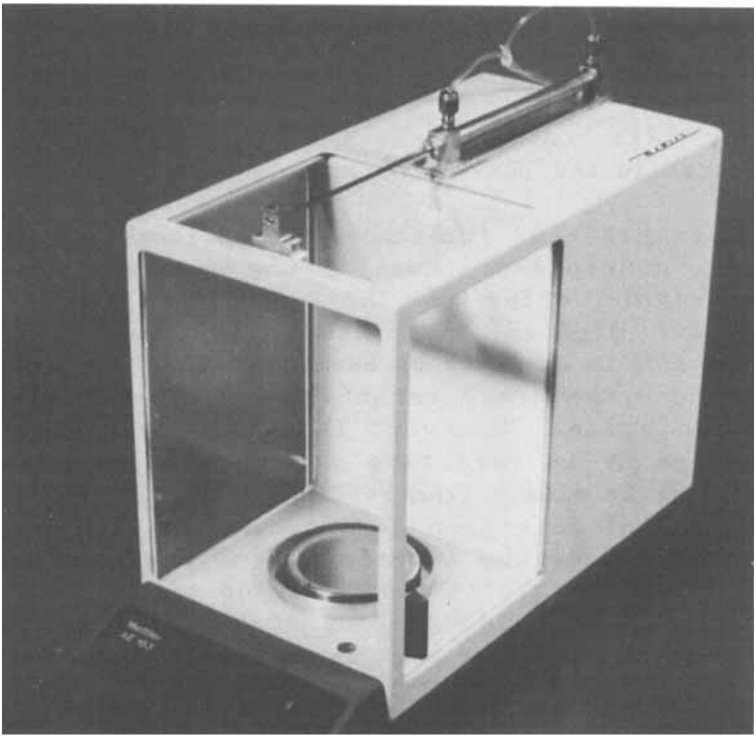


Figure 20. A Mettler analytical balance with an optional pneumatic door opener. The pneumatic piston is controlled by the "Device Controller".

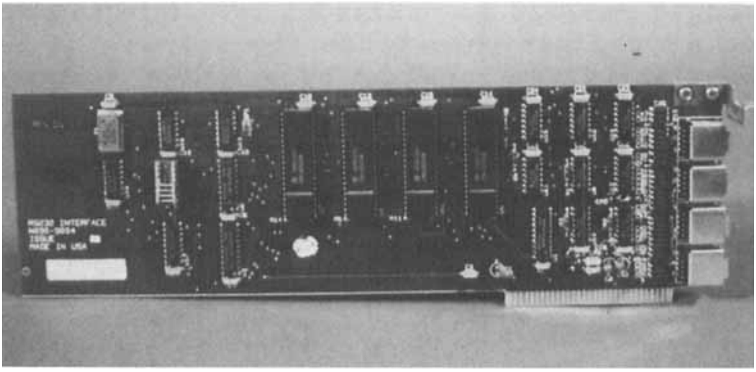


Figure 21. A multiport RS-232 interface card included in the IBM-PC controller.

Up to ten RS-232 interfaces can be installed in the IBM-PC controller. Most of the modern laboratory instruments offer the RS-232 interface as the standard digital interface. The most obvious exception is the case of Hewlett-Packard Instruments which use the HP-IB interface for external digital communication. However, it should be noted that although HP-IB interface is not available as an optional interface from Perkin-Elmer, IEE-488 (HP-IB compatible) interfaces are available from several suppliers and the interfacing of Hewlett-Packard built instruments to the Masterlab system could be achieved through adaptation of the PERL software. Similarly, many other control and measurement devices not specifically designed for the Masterlab robot but designed for the IBM-PC chassis can be easily incorporated into the Masterlab system, (e.g. ADC/DAC boards, temperature measurement and control boards, strain measurement equipment, IBM-PC network systems, chromatographic data systems etc.).

Laboratory equipment without any digital interface can be controlled by a "Device Interface" shown in Figure 22.

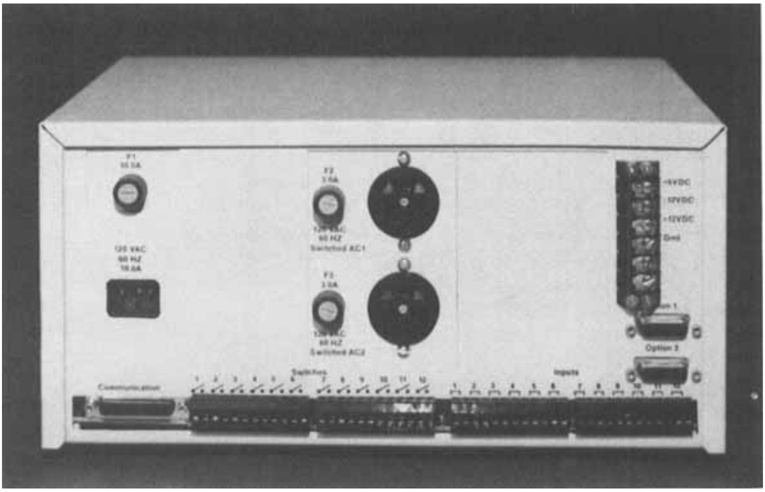


Figure 22. The Perkin-Elmer "Device Interface" is equivalent to Zymark's "Power and Event Controller".

The Device Interface (DI) is the Perkin-Elmer equivalent of Zymark's Power-and-Event Controller and it consists of an array of AC and DC power supplies, digital switch closure and logic input sensors. Similar to the Zymate system, the P.E. Masterlab system offers a pneumatic door opener for the Mettler balance (Figure 20), confirmation devices (Figure 23), a high-quality bar-code reader for sample identification (Figure 24), sample-vial capping station and a number of other useful accessories. GC and HPLC injector stations are also offered (Figure 25).

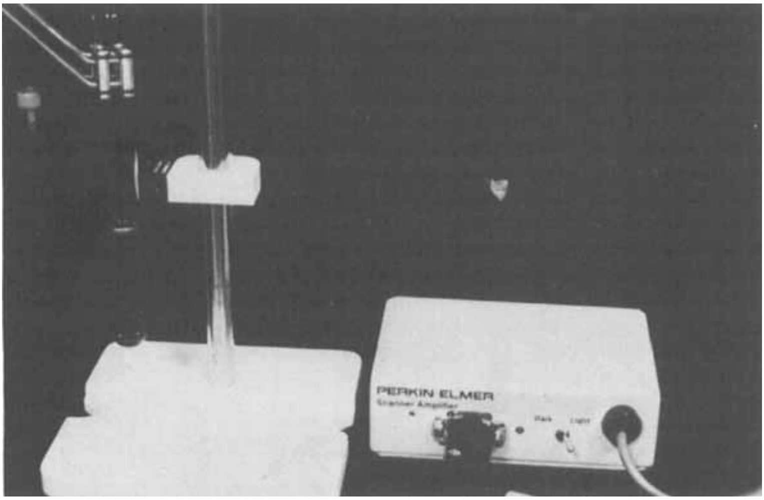


Figure 23. A self-reflective optical sensor. One of the optional confirmation devices in the Masterlab robot system.

Artificial Intelligence in Laboratory Robotics

The use of Artificial Intelligence (AI) in many science and engineering disciplines has been well established and the use of AI in robotics research is already in the process of development in many laboratories. AI research encompasses a very board spectrum of research but a sub-discipline of AI research, Expert Systems, has clearly emerged as an area of high and current interest for many scientists and engineers (12).

Figure 24. A laser bar-code reader in the Masterlab system.

Expert Systems are typically driven by a dedicated Expert System language (for example: OPS5 (13), EMYSIN (14), RULEMASTER (15)) and generally require a large amount of CPU time, memory and disk space. Therefore, future generations of intelligent laboratory robots are likely to be driven by two or more separate processors; one dedicated to the control of the motor-functions of the robot and the other one used to conduct those aspects of the robot operation which involve a higher order, perhaps even cognitive processing.

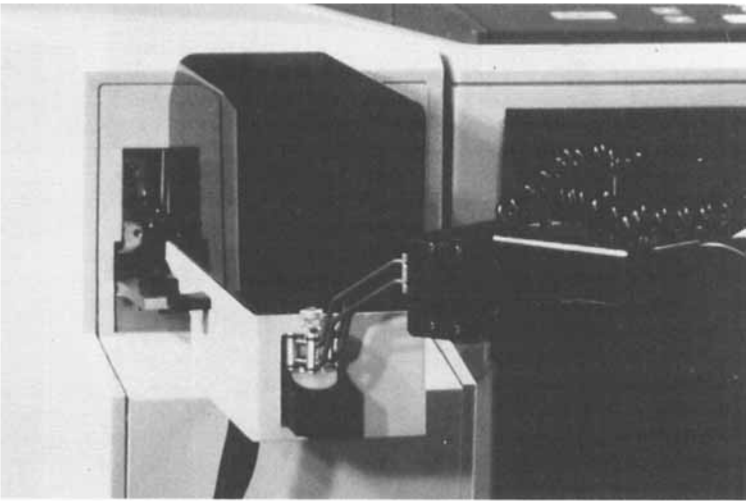


Figure 25. A pneumatically powered GC injector controlled by the Device Interface.

Zymark Corporation now offers an IBM-PC as an optional external computer for the Zymate (II) robot. An IBM-PC (XT or AT) can, in theory, be developed to function as a digital "cortex" for the robot which would process all the heuristic reasoning for the laboratory process.

The Robot Liquid-Chromatographer

To illustrate the versatility of a laboratory robot, the interfacing of the Zymate with an IBM-LC 9533 ternary gradient HPLC, a Varian Instrument Vari-Chrom UV/VIS detector, a Nelson Analytical Model 3000 data station and a Valco air-actuated injection valve is described below. It should be noted that none of the HPLC equipment used in this project is specifically designed for robotics.

Figure 26 presents a block diagram of the system.

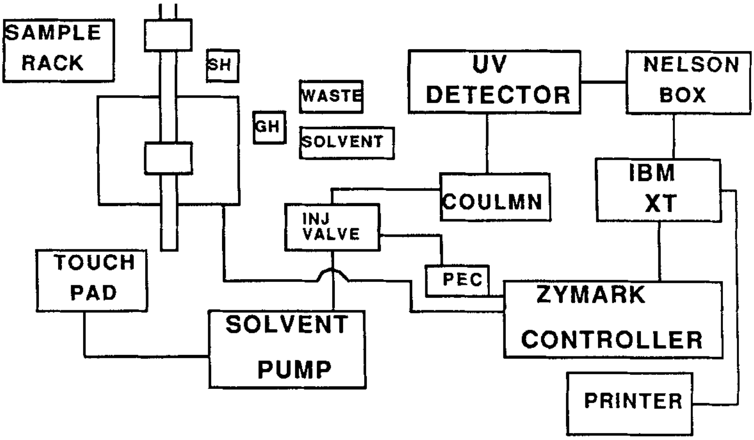


Figure 26. Block diagram of a Zymate/Nelson robot liquid chromatographer system.

The Zymate is taught to program an anchored keypad using a rigid finger attached to the Zymate gripper hand (See Figure 27). The injection valve is actuated by an AC solenoid controlled by two programmable AC power sources at the Power and Event Controller (see Figure 28). The EASYLAB program shown in Figure 12 illustrates the control of HPLC injection by the Zymate. A high-speed 3 µM x 3 cm C18 column is used in this system and the analog signal collected by the UV/VIS detector is process by an IBM-XT/Nelson 3000 data station. The Nelson data station is triggered by the programmable switches at the Power and Event Controller and all the primary chromatographic data are stored in the 10 Megabyte Winchester disk of the IBM-XT.

Figure 27. The Zymate robot programs the keypad of an IBM-LC9533 ternary gradient liquid chromatograph. This illustrates the principle of a "soft" instrument interface.

The Nelson 3000 data station also calculates the resolution of the chromatographic peaks which can then be processed by an optimization routine or AI software in the IBM-XT. This system is still under development in our laboratory but some initial results obtained by the robot liquid chromatographer are shown in Figure 29.

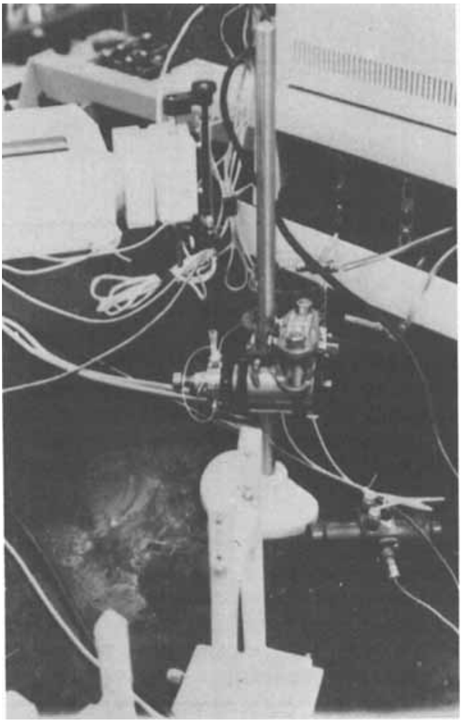


Figure 28. The Zymate operating an HPLC injection valve. The AC solenoid, controlled by the Zymate , is shown at the bottom of the photograph.

This system, in conjunction with a suitable Expert System, could be developed into an automated HPLC methods development procedure similar to "hard automation" solvent optimization systems currently available. However, this robot system, when interfaced to an AI-based computer, has the potential ability to optimize sample preparation procedures and process heuristic knowledge previously obtained from fundamental scientific studies.

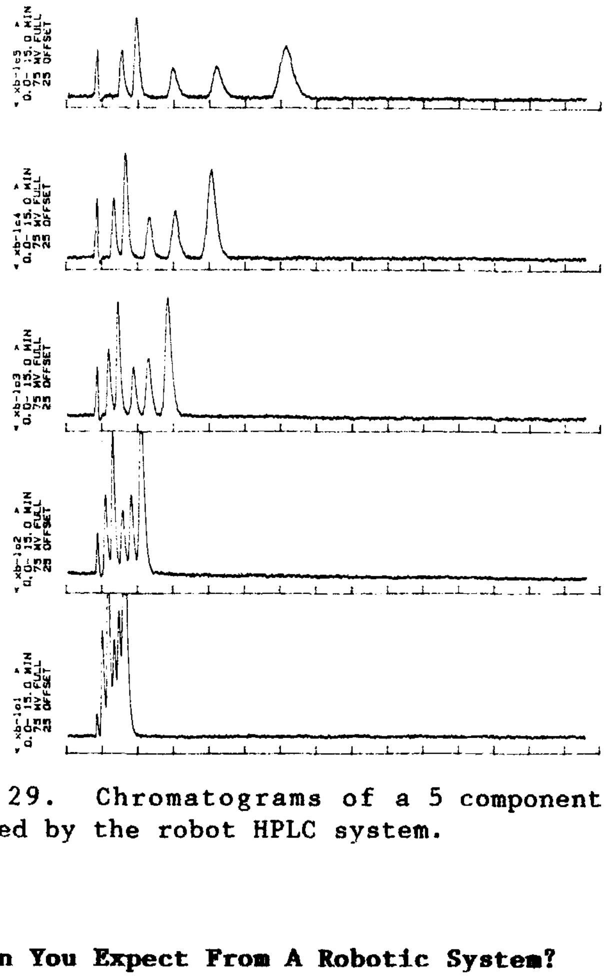


Figure 29. Chromatograms of a 5 component mixture performed by the robot HPLC system.

What Can You Expect From A Robotic System?

After the initial installation of the robot, it must learn the laboratory procedure from an experienced human scientist. Usually a "robot guru" is not needed to train a well designed laboratory robot. Teaching a robot is somewhat similar to training a human laboratory technician and therefore, the person responsible for training the robot should be the person who is already an expert in the laboratory procedures for which the robot will be utilized. We find that an experienced Ph.D. level analytical chemist can learn the syntax and editor of EASYLAB in approximately two hours and become familiar with the operation of all peripherals in about two working days with the aid of the instruction manual. Technicians, undergraduate students and personnel with less extensive knowledge or instrumentation and computer science require slightly more training.

After the initial familiarization period, the robot can be programmed to perform a specific task by a chemist who is already familiar with the task. For a new installation, it may take up to 30 working days before a robot accumulates enough movements to perform a useful task because the location and naming of spatial positions is a time-consuming process. Once the initial programming of the robot is completed, it may take up to three months before the robot will perform extended sequences of laboratory work without committing any errors. Error checking, via microswitches and optical sensors, has to be build into the robotic procedure because the current generation of "blind" robots generally lack sensory perception.

Future Advances

Besides the on-going research in AI, Expert System and motor-control software, technological advances made in the visual and tactile sensory functioning of the robots deserves attention. Some of these technologies are already implemented in the advanced versions of industrial robots and eventually will be available for laboratory robots. Voice-input command and voice-output for the robot can be easily developed with available technology. In the near future, laboratory robots will be even easier to use, will be more cybernetic (perhaps even clever) and will become an integral part of laboratory automation.

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