things written on paper. Implementing a system that does not take that into account is unrealistic (how would you like to deposit your pay check in a bank that had a policy against giving you a receipt?). In one facility I was somewhat surprised to hear that there was no reluctance to work with an automated system. The system designer had done his job right, it did what it was supposed to, and he has a receptive audience for future projects.

(2) Lack of qualified people to design and implement systems. While familiarity with programming in school may prevent someone from going into a catatonic state when faced with a terminal, that does not make him a designer. This needs to be recognized when systems are being designed. The academic community can help this situation by providing for cross-fertilization of computer science people with a bent toward applications with chemistry, the reverse would help equally well. Given the sophistication of the current hardware and software (inside or outside of an instrument), a course or two in Fortran or Basic is not going to suffice. It is also incumbent upon system designers to make sure that systems (a) work and (b) are easy to use, keeping in mind that the end user may be nervous about the use of a system.

SUMMARY

Laboratory automation is beginning to emerge as a discipline of its own. That editorial in the *Proceedings of the IEEE* referenced earlier contains the following statement: "For future laboratory automation systems, there is little doubt that the complexity of the projects will require a considerable team effort....A typical mix of personnel will include instrument experts, persons trained in signal processing and control, and computer scientists or engineers." Every word is as true today as it was then.

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Robotics in the Laboratory

T. L. ISENHOUR

Department of Chemistry and Biochemistry, Utah State University, Logan, Utah 84322

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Laboratory automation has long been an important area where chemistry and engineering have overlapped. Many automated processes now are routine in the laboratory; however, the apparatus that performs these tasks is usually rigid, being designed with only one use in mind. Laboratory robots are flexible automated systems and may well be the scientist's dream of the perfect laboratory technician. Useful laboratory robots are now a reality. This paper will discuss the current state of laboratory robotics in chemistry as well as speculate on the advantages of robots in the future laboratory. The final section will present a project now under way in our research group to produce a flexible robotic system that will be able to design, implement, and evaluate its own analytical procedures.

Laboratory automation has long been an important area where chemistry and engineering have overlapped. Many significant advances have been initiated by analytical and other experimental chemists whose demonstrations have gained the attention of scientific instrumentation manufacturers. These manufacturers have drawn upon the creativity of research scientists and, with their own research and development efforts, produced important instrumentation upon which most laboratory science depends.

Recently, computer data reduction, computer data collection, and computer data interpretation have joined automation as indispensable tools for experimental research. Again, research scientists have pioneered and technologically oriented manufacturers have produced useful systems.

While many automated processes now are routine in the laboratory, the apparatus that performs these tasks is usually rigid, being designed with only one use in mind. A more desirable kind of equipment would be a flexible, automated system capable of performing a variety of laboratory operations including ones yet to be conceived. Laboratory robots are flexible automated systems and may well be the scientist's traditional dream of the perfect laboratory technician. Serious laboratory robots are now becoming a reality and are the topic of this article.

This paper will be divided into four sections. The first will be a brief review of the literature on robotics. Most of that literature will be from areas other than chemistry and often will be references unfamiliar to chemists. The second section

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Thomas L. Isenhour received a B.S. in chemistry from the University of North Carolina in 1961 and a Ph.D. under George Morrison at Cornell in 1965. He was Assistant Professor at the University of Washington, 1965–1969. He joined the Chemistry Department of the University of North Carolina as Associate Professor in 1969, rose to Professor in 1974, and served as Chairman from 1975 to 1980. In 1984, he moved to Utah State University as Dean of the College of Science and Professor of Chemistry. He served as Program Director in Analytical Chemistry at the National Science Foundation during the 1982–1983 year. Dr. Isenhour has directed 23 Ph.D. and 7 M.S. degrees, published over 100 articles and 12 books, and taught an average of 500 undergraduate students annually. He is an Alfred P. Sloan Research Fellow (1971) and was the I. M. Kolthoff Senior Visitor in Analytical Chemistry at The Hebrew University in 1980. Since July 1982, he has been the Editor of the *Journal of Chemical Information* and *Computer Sciences*. In 1983, he won the ACS Award in Analytical Chemistry sponsored by Fisher Scientific Co. His primary research focus is the application of computer methods to problems in analytical chemistry. He has recently initiated a major program in combining developments in artificial intelligence and robotics to produce a computer/robot laboratory director capable of developing, testing, and implementing sophisticated analytical procedures.

will discuss the current state of laboratory robotics in chemistry. The third area will be speculation on the advantages of robots in the future laboratory, and the fourth will be a presentation of a project now under way in our research group to produce a flexible robotic system for the analytical laboratory.

REVIEW OF THE ROBOT LITERATURE

The word "robot" was first used in 1921 by the Czechoslovakian writer Karel Capek in his play *R.U.R.* (Rossum's Universal Robots).[1] Robot was derived from the Czech words "robota", for work, and "robotnic", for serf.[2] In *R.U.R.*, the robots were pictured as mechanically perfect, intelligent beings. The play ended with the robots killing the last of the "imperfect" humans.

Since 1921, the definition of "robot" has changed several times. In the 1973 edition of the Oxford Dictionary, a robot is defined as "a machine devised to function in place of a living agent; one which acts automatically with a minimum of external impulse."[3] The Robot Institute of America, the trade association for robotics, defines a robot as "...a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through a variable programmed motion for the performance of various tasks."[4] While these definitions differ, the operational definition must depend on the task for which the robot is used as well as on the ability of the robot to respond to its environment.

Robots can be divided into three categories based on their evolutionary characteristics: first generation, second generation, and third generation.[5] First generation robots have fixed programs and are best suited for repetitive tasks.[6,7] They do not have the ability to adapt to environmental changes. Most industrial robots are first generation. Second generation robots have sensors such as cameras or pressure- or light-sensitive pads that provide information about their changing external conditions.[8–11] Sensor information allows the robot to adapt to small perturbations in its surroundings. Finally, third generation robots possess features of artificial intelligence.[12–14] This generation of robot is able to respond to environmental changes by modifying its actions. Third generation robots have the ability to solve particular problems that are encountered.

Many automated analytical instruments have been used to relieve laboratory technicians from routine work and to increase their productivity. These instruments are well suited for hospitals and factories, where the same analyses are performed every day. In more sophisticated laboratories, especially research laboratories, where the day to day analyses change, a more versatile instrument is needed. The use of robots in these laboratories has been shown to circumvent problems associated with the nonversatility of automated instruments.[15] The ability of a robot to do repetious or dangerous work, with little or no external intervention, allows almost continuous generation of data and thus increases productivity while decreasing the cost associated with having a human do the same work.

Robots have been used in laboratories in recent years. These robots often do routine work with greater accuracy and efficiency than human technicians. Procter and Gamble uses a robot to perform titrations including the steps of weighing, dilution, and pH end-point determination.[16] At Merck and Co., a robot is used to make reaction mixtures for kinetic studies and then deliver the mixture to a spectrophotometer for analysis.[17] In addition to these tasks, the robot is also used to spot TLC plates with better results. The 3M Co.'s robot is being used to accurately determine the weight per unit area of paper stock.[18] The 3M Co. is also planning a project where the robot will be the integral part in a photographic film preparation technique that must be carried out in darkness. Robots are also used in electroanalytical processes. The Dow Co. uses a robot to screen newly synthesized compounds for electrochemical activity.[19] At Bell Laboratories, a robot is used for its ability to accurately position electrodes in a solution and measure the spatial distribution of pH.[20] In all of these cases, the robots perform manual tasks for the researchers and do not possess any features of artificial intelligence.

CURRENT STATE OF LABORATORY ROBOTICS

Robotics is initially tied to the question of labor economics as is all automation. Machines work consistently, reproduceably, and continuously. Hence, any intelligent management is going to choose to automate, if possible, any process that is currently done by human beings.

A great deal of laboratory automation in recent years has been based upon computerizing the laboratory. Computers, in addition to the advantages listed for other machines above, have the added capability of being able to calculate more rapidly and more dependably and, especially important, to give instructions to other machines. It is this latter capability of computers that is giving rise to what will be the robotic revolution in the laboratory.

To date, robots are limited by their sensing ability and spatial orientation. Current laboratory robots must remain in one fixed location, not being able to move from one position to another. Locomotion is probably not so much the limiting factor on movement but rather the sensing problem in accurately orienting the robot once movement has taken place. Hence, the analytical laboratory robots that have been accepted thus far in the marketplace are all fixed devices that, by dead reckoning from their beginning position, know where they are.

Developments in drive capability that can accurately move a robot arm from one position to another, usually by using some form of feedback to be interpreted by the controlling computer, are the current forefront of robotic engineering research. But if drive capability is the forefront, sensing is the frontier. The really successful robotic manufacturer will be the one that first implements a successful sensing system analogous to sight in human beings.

A great deal of effort is going into the development of "hands" to allow multidimensional manipulation. This gives rise to the use of "touch" sensors that are developing much faster than "sight" sensors. It is obvious that the former is a simpler problem.

Attention has also been paid to the training of robots. Extensive computer programming to perform simple tasks is not acceptable in the laboratory environment. To date, manufacturers are producing simplified programming languages with commands such as "MOVE TO", "ROTATE", etc. However, we are a long way from being able to say "TITRATE WITH HCL", a command that assumes the system not only knows all the intimate steps of a titration process but will choose clean glassware, standardize its own solutions, and so forth.

Two feature articles in *Analytical Chemistry*, by Raymond Dessy,[13] describe available robot systems for the laboratory as of 2 years ago. A survey, by the author, of available products at this year's Pittsburgh Conference (February 1985, New Orleans, LA) showed no startling changes but rather continued refinements of the products already available with one new entry. Perkin-Elmer Corp. is now demonstrating its own system. The decision of Perkin-Elmer to enter this market is significant. As an instrument producer they have always been known for the quality of their products and also for their conservatism in producing instruments only when they are confident the market will be a large one.

The question now is where do we go from here?

FUTURE ROBOT LABORATORY

The desire to develop versatile, flexible robotic systems for the laboratory is prompted by what I call the technician paradox: "Anyone intelligent enough to do the job is too bored to do it right." I suspect the "Peter Principle" applies to the so-called routine laboratory, and competent technicians tend to be promoted to supervisory level positions while incompetent ones often remain in the laboratory.

Consider the advantages of a clinical laboratory that has been turned over to all robot technicians. (We are assuming that robotics will achieve the level necessary to perform all routine tasks in such a laboratory.) First, rare procedures become routine. It will no longer be a requirement that a technician perform a procedure at regular intervals to become proficient. Once "learned", a routine recorded in software will be performed the same way by the same model (or an upward compatible model) of robot 1 day or 10 years later.

Training becomes trivial. No robot will ever be in the postion of saying "The machine who worked here before me didn't tell me anything." One will simply transfer the old software to the new machine, and all the past operations will be instantly known.

Quality control will be very accurately defined. Once the limits of a robotic operation are established by statistical test, future results will be predictable. The "human element", which is the least amenable to statistical treatment, disappears in the robotic laboratory.

Finally, through a central computer dispatcher, a robotic laboratory could have complete coordination of effort. Personality and individual agenda would be eliminated.

To achieve the goal of a robotic laboratory will require the complete integration of computer-based artificial intelligence with flexible robotics. Therefore, in my opinion, robotics will not come into its own in the laboratory until we have intelligent robotics, a topic of much interest in computer science and engineering today.

The question naturally arises as to whether we are ready to couple computer-based artificial intelligence with robotics. I believe we are. There was no new engineering required for Henry Ford to build his factory; only the idea was needed. We currently have the capability to build the cybernetic laboratory; only the idea is needed.

The laboratory of the future may carry out completely computer-controlled cybernetic experiments.

ANALYTICAL DIRECTOR: AN ARTIFICIAL INTELLIGENCE/ROBOTIC EXPERT SYSTEM FOR THE ANALYTICAL LABORATORY

We are undertaking a project in intelligent robotics, not automation. There is a fundamental difference. Laboratory automation is being achieved at a number of levels. In the area of electrical-mechanical transducers, where important progress will be made over the next several years, the solutions will come from creative engineering. Electromechanical devices can already be made that are very accurate. The current Zymate robot arms are reproducible to 0.1 in. and maintain their accuracy over long periods of time.

Important problems remain in the area of sensors. Laboratory robots will remain limited until good mechanical and optical recognition transducers are developed. While our current television and radar capabilities seem excellent, in reality the interpretation is done by human beings and the electrons simply serve to bring the picture to the human eye. Even the most sophisticated widespread system, Air Traffic Control, which has the advantages of limited inputs (airplanes and birds) and well-behaved targets (intelligent pilots flying predetermined courses and aircraft transponders that report code numbers and altitudes), still delivers the radar picture to a view screen for human interpretation.

We plan to combine recent developments in laboratory automation and computer methods toward the creation of a robot/artificial intelligence system we shall call an Analytical Director. We propose to demonstrate that an Analytical Director can develop, test, implement, and interpret chemical analysis procedures. Further, we propose to demonstrate that the Analytical Director can learn from its own experience, can learn from the experience of others, and can communicate what it has learned to others. It is a misconception that the best use of robots will be exhaustive testing of possible solutions to problems. While computationally exhaustive methods are often quite successful, they are rarely useful to analytical chemistry. Artificial intelligence is required for a real breakthrough in automated laboratory methodology.

Consider the following analytical problem that might arise from a relatively simple problem. Given: 10 possible components to a mixture; 10 reagents; 10 possible temperatures; 10 pH values.

If each reaction combination were chemically independent, that is, the results of any combination could be learned by a linear addition of the separate tests, then 10 000 procedures could be carried out to determine the entire system. This might be feasible if, for example, each test could be completed in 1 min. (This would require just about 1 week of continuous work assuming the robot suffered no maintenance problems or other delays.)

However, chemical reactions are not usually independent. For example, if one of the components were Fe(III) and two of the reagents were SCN^- and citrate ion, there would clearly be complex equilibria interactions. If we redo the calculation considering from 1 to 10 possible components, from 1 to 10 possible reagents, and any combination of 10 temperatures and 10 pH values, it requires 1.63×10^{15} tests. Again carried out at 1-min intervals, assuming the robot could work through the entire set of procedures without interruption, 3.10×10^9 years would be needed. Experimental design methods might achieve a few orders of magnitude improvement but nothing like the 10 orders of magnitude necessary to make this approach feasible.

Futhermore, in real analytical situations the number of variables and dimensions is often much greater. It is clear that analytical chemistry cannot be done by exhaustive trial and error. Therefore, if robotics is to have any real effect upon the field, an intelligent robot must be created that can choose meaningful experiments and profit from its experience as well as the experience of others.

We propose to construct such a system and test it initially on a very limited analytical problem to prove that artificial intelligence can be used to seek efficient paths to complex analytical problems without resorting to exhaustive trial and error. To do so, our first model system will be very simple, involving three ions, five reagents, two temperatures, and three pHs. This system can be exhaustively tested with 4320 procedures. Assuming 1-min tests, 3 days would be required. Exhaustive testing of this model system will produce a set of observations that will facilitate the development and testing of generalized data structures and optimization routines to be used by the Analytical Director for more complex problems. For complex problems, the Analytical Director must develop artificial intelligence methods that circumvent the testing approach.

We have selected a developmental domain that is a closed system of simple analytical chemical problems. The domain will be wet and photometric analysis of simple cations. The set of manipulative skills required is purposely limited to the abilities of the Zymark-type system, and the chemical reactions and spectrophotometric measurements possible are limited to those that can be performed with the available equipment. This way, we plan to be able to test thoroughly the creative capabilities of the artificial intelligence programs to be developed for the Analytical Director. We have further selected the domain of water analysis for an advanced test of the Analytical Director. Only by using an unbounded problem will we be able to demonstrate the true capability of the Analytical Director.

Given a set of standards, reagents, and manipulative skills, the Analytical Director will develop its own set of tests for each individual cation. These data will be stored in a relational data base keyed on ions, reagents, conditions, and results of spectroscopic measurements. It will be assumed initially that no chemistry is known for these elements or reagents. After developing possible individual tests, these tests will be cross compared to identify likely interfering reactions. Tests will be characterized by their quality as defined by time, expense, and reproducibility. As the best compromise of these components is a value judgement, an adjustable value coefficient will be developed. Then possible mixture methods will be systematically tested and compared for success. As this proceeds, the relational data base will continue to expand. Finally, new unknowns will be introduced into the system to test the ability of the Analytical Director to adapt to new circumstances. At this point, literature information will be added to the data base. The Analytical Director will thereby "learn" from the experience of others. Further, the Analytical Director will report developed procedures for possible use by others.

SUMMARY

Robotics is rapidly becoming important in laboratory science. Many routine processes can be performed better and quicker by automated robotic systems. However, robotics offers much more than ordinary laboratory automation. The coupling of modern robotics hardware with artificial intelligence software offers a new approach to experimental science. Future systems will be able to design, perform, and evaluate their own experiments. The result should be the scientist's age-old dream of the perfect laboratory technician.

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