Brewing Laboratory Automation. A Review with Special Emphasis on the Use of Microcomputers[1]

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ABSTRACT

Most laboratory procedures contain the same seven stages; various automation approaches address different combinations of these. Automation of major instruments or the use of programmable calculators, computers, continuous flow analyzers, or programmable analyzers can improve efficiency in one or more of the steps of a procedure. The usefulness of each of these techniques in a brewing laboratory is discussed. General-purpose microcomputers provide a particularly attractive approach to automation because they can be applied to many different procedures and to most of the stages of an analysis.

Key words: *Analysis, Computer, Data evaluation, Data storage and retrieval, Programmable calculator, Report generation*

The possibilities of automating various laboratory operations have been of interest for some time. Automation improves precision by minimizing variations in the application of a procedure and can lead to a significant improvement in analyst productivity. In the past, automation has generally meant committing a piece of equipment to one particular purpose for a long period of time. This is justifiable in a situation in which many samples are to be analyzed by a single procedure. Most brewing quality assurance functions, at least in the author's experience, tend toward the opposite extreme; a relative handful of samples are to be analyzed by a fairly large number of procedures. Recently the cost of computing equipment, particularly that based on microprocessors, has fallen to the point that "intelligence" is incorporated into most newly designed instruments. The same cost reduction applies to small general-purpose computers, and this makes attractive another approach—the use of a general-purpose computer to control and acquire data from nonintelligent instruments.

This article outlines the automation possibilities available today, shows how microcomputers fit into the situation, and outlines some of their possible uses.

STAGES OF AN ANALYSIS

Any laboratory procedure consists of a number of steps. Usually they include most of the following: 1) sample preparation, 2) the analytical procedure, 3) observation of results, 4) data storage and retrieval, 5) calculation of results, 6) data evaluation, and 7) report generation. It is worthwhile considering what is involved in each step and whether or not it is automated by a particular approach.

Sample preparation includes drawing a sample from a source or a larger sample, obtaining a known amount of it (usually by weighing or pipetting), and possibly performing other treatments such as grinding. In many cases extraction may also be required. Some samples, such as beer or wort, require other pretreatment such as decarbonation or filtration.

The analytical procedure itself is performed by the analyst by a nonautomated method. Typically such procedures consist of a measurement step applied to a previously prepared sample. This can be fairly simple, such as making an optical density measurement with a spectrophotometer or a pH measurement with a pH meter. In some cases the procedure is more complex and labor intensive, such as performing a titration or adding one or several reagents and then mixing and heating before an instrumental measurement.

Observation of results may be very simple—eg, reading a meter or burette for a single point that defines a property of the sample, or more involved—eg, making a number of observations for each sample, as is required in the conductometric titration of hop α-acids. With chromatographic data, a measurement on a chart may be required, such as the height or area of a peak.

Data storage and retrieval, although listed as the next step of a laboratory procedure, does not fit neatly into the chronology with the other steps. In many procedures, observations are stored when they are made (usually in a laboratory notebook); they are later retrieved for calculations, the results of which are stored and retrieved for data evaluation and report generation.

Determining the results of analytical procedures generally requires some calculations to yield the analyte concentration. This usually means that results obtained with standards are applied to produce a calibration curve, from which the analyte concentration in an unknown sample is obtained. This is frequently done mathematically rather than graphically.

The results obtained from an analysis are usually evaluated by the analyst, or the supervisor, in terms of the history of past results. This may or may not be a conscious process, but it certainly exists. A result outside the expected range will be questioned, the calculations will be checked, and quite frequently the analysis may be repeated before the result is reported.

Report generation is the final step. The corrected results are generally committed to paper and disseminated in some way. This is primarily a secretarial or clerical function, although it may involve an analyst transferring numbers from a notebook or a calculator tape to a form that is either distributed directly or typed. This might be done when the form has been completely filled in or at some predefined interval (before a meeting, for instance). "Report" is used here in the sense of being the final form in which a result leaves the laboratory, not merely a printed result produced as the output of an instrument.

AUTOMATION POSSIBILITIES

Several different kinds of laboratory automation are possible. Most of these perform from two to four of the seven steps outlined above. Various automation approaches are compared here on the basis of their suitability for use in a brewing laboratory.

Automation of Individual Instruments

Perhaps the simplest approach to automation is to equip major instruments with the facility to automatically process a series of samples or to perform some calculations. This is particularly common for chromatography, in which automatic samplers are attached to gas chromatographs or liquid chromatographs. Very often electronic integration is also used to make peak area measurements. Although sample preparation is still required, such an automated instrument can operate around the clock unattended. Many integrators can perform involved calculations and produce a printed tape of results in concentration form. This automates four of the seven steps: procedure, observation of the results, data storage and retrieval, and calculations.

Automation of other types of major instruments is fairly commonplace. These may include ultraviolet and visible spectrophotometers and atomic absorption spectrometers, with automatic samplers and digital printers to permit unattended operation. Significant productivity gains are possible in this manner because the analyst can prepare more samples during the

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time the instrument is in operation. Further, precision is often improved because many variations among samples caused by human variations in technique are eliminated (ie, degree of washing of cuvettes or cuvette placement in a spectrophotometer). The steps automated in such cases are the same as for the chromatographic instruments above except that calculations or data storage and retrieval may not be performed.

Accessories to add reagents to samples and then introduce the mixture to a spectrophotometer for kinetic measurements are available from a number of instrument manufacturers (including Gilford, Perkin-Elmer, and Pye Unicam). This kinetic approach usually includes automation of the analytical procedure and observation of results. It could be applied to many brewing methods currently done as equilibrium determinations.

Analyses with titration end points can be done with automatic titrators of several possible levels of sophistication. In some cases a beaker containing the sample is placed on a platform, the titration is done automatically, and the end-point value is displayed or printed. With more expensive titrators, a number of sample beakers can be loaded on a carousel. These are automatically moved into position and titrated in turn.

The sort of major instrument automation described here is generally worthwhile in any industrial laboratory, as it clearly increases productivity and in many cases can make use of instrument time not otherwise available (lunch hours, overnight, weekends). Such automation is generally only semiautomatic, as very often extensive sample preparation steps are required before the sample is presented to the automatic instrument (ie, sample weighing or pipetting, reagent additions, and color development before the tubes are put in a spectrophotometer autosampler). In some cases an automatic or manual dispenser can be used (to add reagents) or a diluter (to draw an aliquot of sample and add reagent) to rapidly prepare a sample set. As Buckee has noted (5,6), this semiautomated approach is particularly attractive in the brewing laboratory because samples can be handled in parallel and speed is increased over that of sequential procedures. An example of this would be the use of an automatic diluter to place sample (or in some cases standards) and reagent in each of a number of tubes in a rack. The analyst then may place the rack of tubes in a water bath for a prescribed time interval, use a dispenser to add another reagent to each tube, mix them, and place the tubes in an autosampler that feeds a colorimeter at a high sampling rate. In this way the high sampling rate of parallel sample processing is maintained, and two or three pieces of partly automated equipment can be used for many different procedures.

Automated operation of major instruments generally covers a part of the analytical procedure and the observations of results. If a printer is employed, it may contribute to data storage and retrieval, as the printed tape from the instrument can be placed in the analyst's notebook. In cases where integration is employed, some calculation of results may also be done.

With the latest generation of instruments, most of which contain built-in microprocessor "intelligence," the ability to self standardize, build linear or even nonlinear calibration curves, and present corrected results has often been included. This has also led to integrated chromatography instruments that can be instructed to analyze, say, the first 12 samples by one procedure and the next five by a different one. At least one of the available instruments for high performance liquid chromatography (HPLC) can be instructed to chromatograph each sample under different conditions. This is a great boon in method development work.

Automation of Calculations

Another approach to laboratory automation is the use of a programmable calculator (24,25) or computer (28) to perform calculations. This is most beneficial when the calculations are complex. Programs can be specially tailored to the manner in which analyses are performed in a particular laboratory, including the use of standards of certain values to produce a calibration curve (linear or otherwise) or the inclusion of positive and negative controls in the sample set. This may be combined with data storage and retrieval (primarily when a computer rather than a calculator is used), with data evaluation (by checking to see if results are within an expected range), and even with report generation, depending on the system used. A large computer can store the results of different analyses performed on the same sample in a file and automatically generate a report when all have been completed.

Segmented and Continuous Flow Analyzers

Historically, the clinical chemistry field has provided the largest market for development of automatic analyzers. This began with the Technicon type of air-segmented flow procedures (11,27). In the simplest form, a sample changer supplies a sample to a peristaltic pump, which provides the driving force to add it, and air bubbles, to a flowing stream of color reagent. The resulting solution is mixed, heated, and passed through a colorimeter. The output is provided by a strip chart recorder. The final measurement is the peak height, ie, the linear distance between the baseline (between samples) and the top of the peak. Many other kinds of detectors such as ultraviolet spectrophotometers, fluorometers, atomic absorption spectrometers, specific ion electrodes, heat detecting instruments, etc., can be substituted for the colorimeter. Various specialized modules for performing operations such as dialysis, extraction, and distillation can also be included. Many of the analyses of interest to brewing laboratories have been automated in this way, including determinations of acetoin (6,13), total acidity (13), alcohol (6,13,17), α-amylase (3,13), amino nitrogen (3,6,13), total carbohydrate (3,6,13), copper (13), diastatic power (3,6), β-glucanase (3), iron (13), isohumulones (13), original gravity (17), phosphorus (13), polyphenols (3,4), polyphenol oxidase (3), fermentable sugars (6,13), reducing sugars (13), sulfur dioxide (6), total nitrogen (6,13,31), and vicinal diketones (6,13,30). The segmented flow methods are performed with fairly inflexible systems. They are best suited for situations in which quite large numbers of samples (typically 10–60 per hour) must be analyzed by the same procedure, as in the screening of new barley varieties (3). In this situation, the small sample size requirement is an additional benefit. In some brewing laboratories, the large number of samples for a particular determination makes this type of analysis practical (30). For most brewing laboratories, however, the number of samples to be examined by a particular method cannot justify the cost of this type of automation.

A number of improvements have been made to segmented flow systems to make them more flexible. Interchangeable platforms containing reagents, plumbing, and tubing can be used with newer pumps so that different procedures can be performed with a single sampler, pump, colorimeter, and recorder. Samples can be accumulated and analyzed in large batches by different procedures on subsequent days. Buckee and Hickman (6) pointed out several disadvantages of this approach for a brewing laboratory, most notably that many samples of interest in brewing lack either microbiological or physical stability. Buckee also stated that traces of reagents from one procedure can remain in the system even after prolonged washing and that significant time is required for a system to reach a steady state on startup (5). He felt that the series approach (rather than parallel) is slow and leads to problems of long-term drift. This is usually guarded against by the insertion of standards after a number of samples.

Continuous flow analyzers of the type described perform the analytical procedure and observation steps of a method. In cases where little or no sample treatment is needed before analysis, as with wort and beer in some determinations, the sample preparation step appears to be minimal, but someone must still draw the sample, see that it is correctly identified, and place it in a beaker on the autosampler. Recently various add-on features, such as digital printers and microprocessors, have become available for segmented flow equipment. This extends the capabilities of the system to include calculations, with temporary storage of data

between analysis and calculation. Depending on the system, the analyst must still perform from three to five of the seven steps of a procedure.

A very recent development is the use of flow injection analysis, or FIA (21,23). This is also a flowing stream approach, but without air segmentation. Sample throughputs with FIA are significantly higher (200–300 samples per hour) than with segmented flow systems; this is possible because measurements are performed kinetically, without waiting for equilibrium to occur. At first glance, FIA would appear to be even less suitable for brewing applications than the other flow approach. However, system startup and stabilization is said to be very rapid with FIA (21). This means that if a system is easily reconfigured, it could be set up for one procedure for 1–2 hr and then changed to another for a similar time and so on.[2] In this case, the high throughput would make it attractive for a brewing laboratory. No brewing analyses by FIA have been published at this time, although the technique is undergoing testing in at least one laboratory.[3] Many quantities of brewing interest have been determined in biological materials with FIA. These include total nitrogen content in plant digests (29), glucose in blood (15), sulfate in plant digests (16), nitrate in environmental samples (14), and calcium, magnesium, and potassium (32) and iron (10) in plant material.

FIA equipment can be fairly simple, encompassing only the analytical procedure and observation of results, or it may, like segmented flow systems, include observation of results and calculations.

Programmable Sequential Analyzers

Some programmable analyzers have been developed that can contain a few or many different reagents at one time. One of a number of procedures, which can be either equilibrium or kinetic, can be selected, and the instrument will perform the desired procedure on a sample or samples. In some cases such instruments are designed to be supplied with standards of varying concentrations and to construct a linear or even nonlinear calibration curve as appropriate for a particular procedure. The results for all the unknown samples are then obtained from this curve and printed automatically. After the first procedure has been performed, the instrument can very simply be instructed to perform a different procedure and requires no changes in reagents or equipment. Most such systems were originally developed for the medical field, but in the last few years industrial models have been offered.

The Kem-O-Mat™ (Coulter Electronics, Hialeah, FL) performs either equilibrium or kinetic colorimetric methods. With this unit, the analyst inserts a cartridge tape describing a given procedure and a serum vial containing the appropriate reagent in the apparatus. The instrument stores all test results, performs calculations, and prints the results. A larger, more highly automated unit, the Coulter® Kem-O-Lab can perform from one to six different colorimetric tests on each of 120 samples unattended (7). As many as 240 samples per hour can be processed (six methods each on 40 samples).

The Digichem 4000® (Ionics, Inc., Watertown, MA) is available in three versions: for titrations, colorimetric analyses, or selective ion electrode procedures. Methods are selected by thumbwheel switch, and either a single or several different analyses can be applied to each sample. Quite complicated procedures and data treatments can be performed.

The Industrial Quantitative Analytical System analyzer (American Monitor Corp., Indianapolis, IN) can perform as many as 31 different colorimetric procedures, with analysis rates as high as 400–750 per hour. No changing of reagents or tubing is required in order to change procedures. The results are printed after calculations and can be stored for later recall. This analyzer has been reportedly used for a number of procedures on beer and brewing materials, including iron, chloride, vicinal diketones, sulfate, sulfur dioxide, phosphate, ammonia, copper, hardness, fluoride, calcium, alkalinity, aluminum, color, glucose, and amylase (1).

Programmable sequential analyzers thus perform the analytical step, observe the results, perform calculations, and may also provide storage and retrieval of data. They span a wide range of cost (roughly $30,000–$100,000) and convenience.

Automation Possibilities with Existing Instrumentation

Although many newer instruments are to a large degree automated or fairly easily automatable (ie, have a digital display and/or a binary coded decimal output), many older and perfectly serviceable instruments are not. In some cases the control of older instruments can be automated with a general purpose programmable control unit. This offers possibilities of experiment control, data logging, calculation, and report generation. Several approaches can be taken here.

A data logger is essentially a passive device that monitors signals of one or many instruments, converts these into numbers, and periodically prints the results on a paper tape. This is essentially the digital equivalent of a multipoint recorder and automates only the observation step.

Some available devices will take an analog signal or signals from an instrument and generate a digital output that can be fed to a computer or programmable calculator. One example of such a device is called the SmartFace (2); this, like a data logger, does not permit control of an instrument but does allow monitoring of its output. The computer or calculator can then store and retrieve data, perform calculations, and may be used to evaluate results or generate reports.

A large mainframe computer can be used to log data and control apparatus either directly or through an interfacing device such as the Device Coupler sold by IBM. The latter is easier and safer as it does not require that the large computer always be functioning and instantly available. It also greatly simplifies the connection of instruments to the computer, as it provides the necessary electronic interfacing. The Device Coupler costs over $3,000, however.

Yet another approach is the use of a mini- or microcomputer in the laboratory directly interfaced to various instruments. This permits real time control of the experiment, observation of results, calculation, data evaluation, and in some cases data storage and retrieval and report generation. Minicomputers typically cost $12,000 or more, but microcomputers with the necessary features can be purchased for as little as $1,500.

Microcomputer Possibilities

Only a few reports in the brewing literature have described the use of general-purpose microcomputers to automate laboratory procedures (18,22,26), and these have been quite specific applications. This concept will be described here in some detail.

Because a microcomputer (a computer based on a microprocessor) is the least expensive type of computer available, it is the most attractive, providing it can do the job conveniently enough. Teaming a computer, which is the most flexible instrument, with laboratory equipment permits a large range of possibilities. The main strength of a computer is its programmability. When it is connected to one set of equipment and supplied with one program, it can perform one particular function; when connected to another set of equipment and supplied with another program, it can perform an entirely different function.

Some of the functions readily handled by a small computer include making titrations of various kinds (conductometric, pH end point, colorimetric end point, redox, or specific ion [8]) and performing, as a gradient programmer for HPLC, a multichannel data acquisition and logging system, a kinetic analyzer (19), and a general purpose timer, sequencer, and controller for many types of experimentation.

[2]Concept from a private communication with G. Buckee, Brewing Research Foundation, Nutfield.

[3]Private communication. I. Rosendal, United Breweries, Copenhagen.

In any of these applications, the speed and convenience of the computer make possible much more sophisticated data treatment than would be the case with simple sequencing automation. Typically, when an observation is made in a conventional analysis, one number is observed and entered into a notebook. If some random noise is present and either a meter needle or a digital display is oscillating, this procedure is somewhat subjective and prone to error. A computer, which is able to make several hundred observations in a second, can take a number of data points and average them to minimize the effects of random variation. Even more involved techniques (20) can be applied if necessary, either to simulate any kind of analog noise filtering, to perform digital filtering (ie, absolute band pass), to employ one of the very sophisticated statistical treatments developed to remove noise with minimum loss of information from a rapidly changing signal (signal frequency response is curtailed by ordinary noise filtration techniques), or to correct for background interference (12).

Because the ability and patience of a human analyst to copy numbers into a notebook and later key them into a calculator is limited, more data points can generally be taken with a computer. This is useful in a titration, for instance, where the accuracy of estimation of the end point can be improved with more data. Very sophisticated data treatment is also possible, which need not be understood or even apparent to the operator. For example, the end point of a titration curve is often defined as the point of most rapid change, or steepest slope. Although this can be detected directly from titration data (voltage versus volume of titrant added), the computer can also calculate the first derivative of the titration curve (voltage change per volume of titrant added versus volume of titrant added), which has a sharp peak corresponding to the point of greatest change. This provides a better defined, more precise way in which to detect the titration end point and is far more accurate than an analyst's impression of the first appearance (or disappearance) of color.

Required Features

The features required for a laboratory computer are quite modest and inexpensive. Although programming can be done in machine or assembly language, this is a very slow and tedious, and the ability to program in some high-level language such as BASIC is a practical necessity.

The capacity to store and load programs is needed and can be served by an audio cassette recorder employing ordinary cassette tapes. A system based on magnetic disks is more powerful and convenient to use, especially when data storage and retrieval and report generation is desired, but it is not needed for most laboratory functions and will at least double the price of a microcomputer.

The ability to communicate with the computer is a fundamental requirement that can be satisfied with either a keyboard or a terminal of some sort. To generate reports, either a printer or a hard-copy (teleprinter) terminal is needed, and the computer must have the ability to communicate with whatever is to be used. The above items are all fairly standard computer peripherals.

Additional special features are needed to enable a laboratory computer to communicate with and control instruments. The primary need is the ability to convert a voltage signal from a laboratory instrument into a digital number. This is done with an analog-to-digital (A/D) converter. A/D converters come with varying capabilities of speed and resolution; for microcomputer application, higher speed is perhaps best, although this usually means lower precision, which can be compensated for by averaging many successive observations to obtain a single data point. A multiplexer is quite commonly used with an A/D converter. This is a digitally controlled switch placed before the A/D converter to supply it with different input signals on command. Thus one A/D converter can sequentially monitor eight, 16, or even more voltage inputs.

A requirement for many laboratory applications is a real time clock. The computer must be able to measure elapsed time, like a stopwatch, and also to perform operations at defined time intervals. Many computers lack this timing ability as a basic feature and require an accessory to perform it.

To control instruments and experiments, the computer must be able to turn things on and off. This is the function of digital (on-off) output ports. These cannot directly switch much current although they can be connected to instruments with transistor-transistor logic level signals (5 VDC at low current). Higher voltages and currents can be switched by the use of solid state or conventional relays driven by the computer output port. This interfacing job has been simplified greatly by the recent development of modules that can be directly connected to a computer output port to drive, for instance, 110 VAC at currents as high as 5 A.

For the computer to sense the condition of equipment (when a

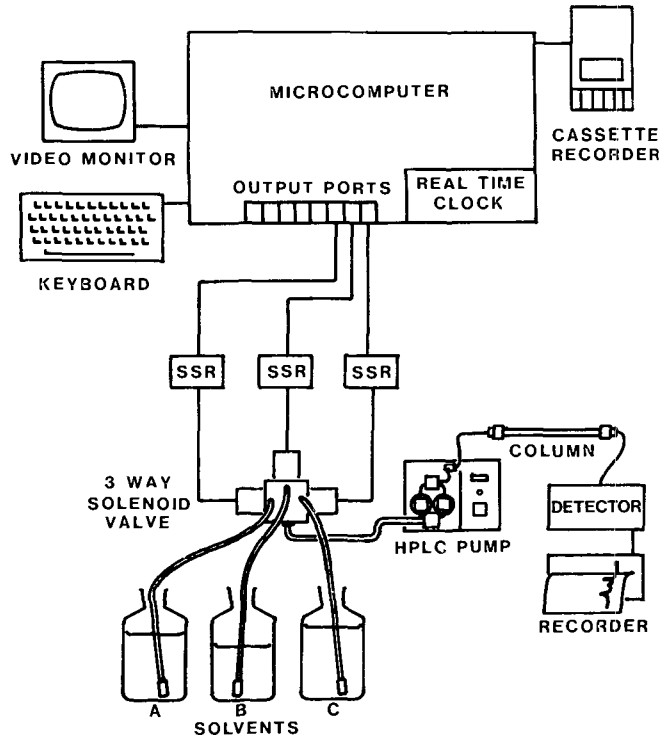

Fig. 1. A microcomputer used as a solvent gradient programmer for high performance liquid chromatography. **SSR** = solid state relay.

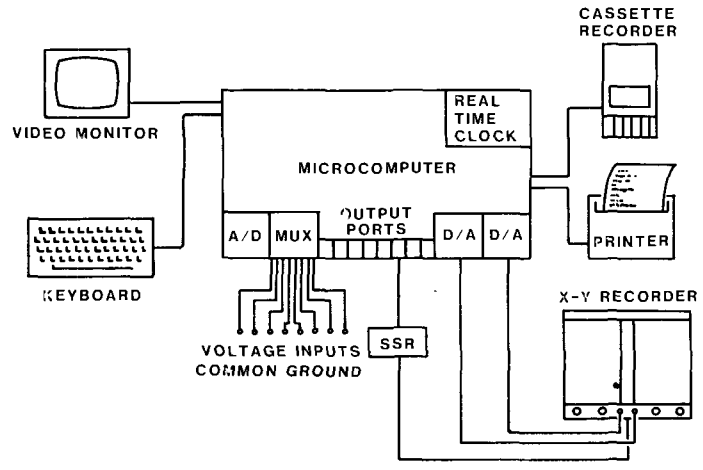

Fig. 2. Data acquisition system using a general-purpose microcomputer. **MUX** = multiplexer, **A/D** = analog-to-digital converter, **D/A** = digital-to-analog converter; **SSR** = solid state relay.

pipetting device is out of titrant, for instance) or to accept binary coded decimal data from an instrument, it must have digital input ports. Often, signals are coupled to the computer input ports by the use of input connection modules. These permit the computer to sense when a 110 VAC circuit is energized, for instance.

An additional feature that is very convenient, although not absolutely necessary for most automation functions, is digital-to-analog conversion (D/A). A D/A converter can be used to produce a voltage proportional to some calculated number to drive a piece of equipment (such as a temperature controller or a mechanical drive). Two D/A converters can be used to drive an X-Y recorder for plotting. This permits scaling and plotting of data observed by the computer.

A few examples may help to clarify some of the functions that a microprocessor might perform in the laboratory.

A fairly simple application is a gradient programmer for HPLC (Fig. 1). The only control function required here is the switching of three solenoid valves on the low-pressure side of the HPLC pump. The programmer simply alternates selection of solvents A, B, and C for short time intervals. Any desired gradient shape (linear, curvilinear, stepwise) can be selected by programming. The real time clock measures time intervals, and output ports turn the valves by switching line current with solid state relays. To produce 50% solvent B in solvent A, for instance, solvent B might be selected for 1.0 sec followed by solvent A for 1.0 sec. This would be continuously repeated until the gradient changed from this value. For 75% B in A, the valve might be repeatedly turned to the B position for 1.5 sec and then to the A position for 0.5 sec, and so on.

A multichannel data acquisiton system (Fig. 2) requires a real time clock and has the ability to measure the voltage outputs of a number of instruments, using a multiplexer. In the simplest case the data might be sent to a printer, which would list the observed values for each channel at specified time intervals. The computer can easily correct and scale each of the input channels so that the printer values represent the observations in convenient units (ie, thermocouple voltages could be converted to temperature in °C, even though this is not a linear relationship). For added convenience, the data can be plotted with each channel scaled to display either its full voltage range or the maximum observed variation as full scale on the chart. One output port is used to control the pen lift and a D/A converter is needed for each of the two recorder channels.

A titrator that is far less expensive than a commercial unit can be made with a microcomputer, a repeating dispenser, and a pH meter (8,9), as shown in Fig. 3. An output port triggers the dispensing of a drop of titrant through a solid state relay. A pH (or other type) electrode senses a change, and an analog voltage proportional to the change is supplied by the pH meter to the A/D converter of the microcomputer. The process is then repeated, and the computer senses the titration end point and prints the result calculated as analyte concentration in the original sample. If desired, a plot of the titration can be produced with the X-Y recorder.

Simple laboratory instruments can thus be made into powerful automated systems for a given analysis and readily reconfigured for another procedure. This form of automation has almost limitless possibilities in both research and quality control applications.

OVERVIEW

Each kind of automation is attractive in certain situations. Different approaches vary in their capabilities to automate the steps of a procedure (Fig. 4). The sample preparation step is almost never automated because, as a minimum, a portion of a larger sample is nearly always weighed out or pipetted. The only exceptions here are when a direct concentration measurement can be performed on a solution (pH, for instance) or when a sample is preweighed by definition (as with pharmaceutical tablets). Most approaches automate either the chemistry (the analytical procedure and observation steps) or the data handling portions (data storage and retrieval, calculations, data evaluation, and report generation) of a procedure. Recently, a distinct tendency to broaden this coverage has been evident. Manufacturers of laboratory instruments are offering accessories or building in the

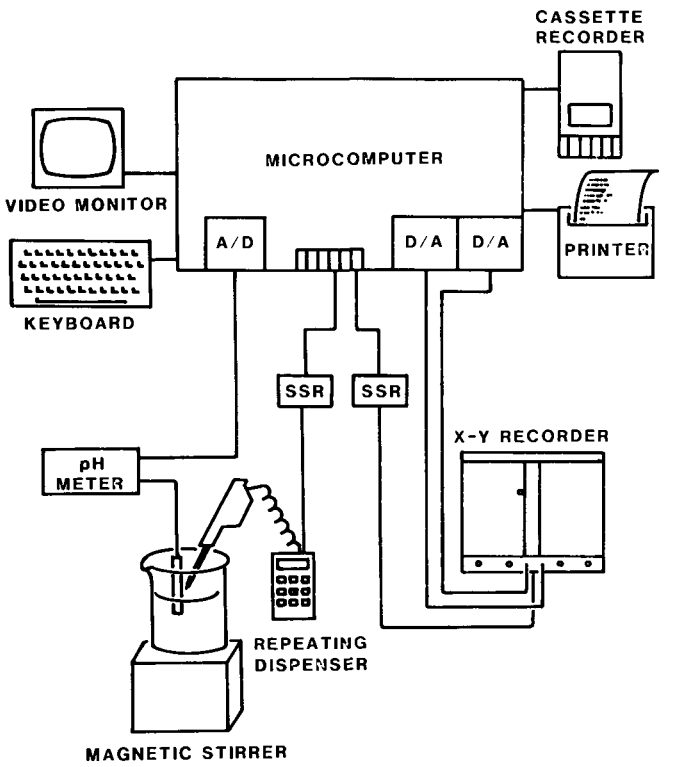

Fig. 3. A titration system operated by a microcomputer. **A/D** = analog-to-digital converter, **D/A** = digital-to-analog converter, **SSR** = solid state relay.

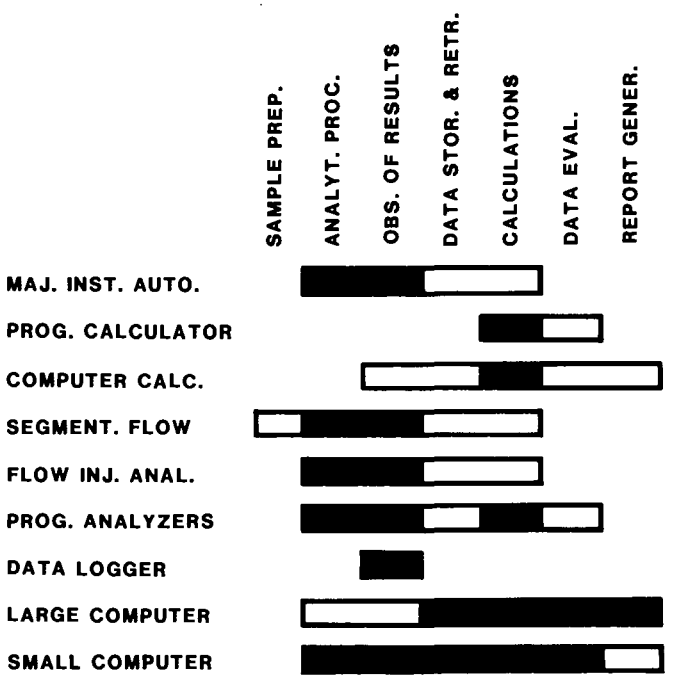

Fig. 4. Methods of laboratory automation, showing the parts of an analysis normally (solid bars) and sometimes (open bars) automated by a particular method.

capability to perform complex calculations, often with data storage and retrieval. Interfaces offered for programmable calculators and computers are making them much easier to connect to instruments. The open bars in Fig. 4, indicating "sometimes automated," depict this situation. Both directions lead to greater information handling by single systems, which results in less analyst time spent transferring, storing, and retrieving information, and less possibility for introducing errors at each step.

Small computers coupled with existing laboratory equipment can readily perform five or six of the seven stages of an analysis. Further, they are capable of communicating with other, higher level computers, using virtually any desired protocol for data storage or report generation.

The brewing laboratory of the future is likely to evolve into a network of intelligent instruments and small instrument control computers communicating with a data-base-managing computer that will log in each sample as it arrives and issue interim and final reports as required.

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