A microprocessor-based system controlling a nuclear demagnetization refrigerator is described. Magnetization, precooling, and demagnetization are software-controlled as are heat and persistent current switches. Although the system is fully automatic, the user maintains the ability to alter the process at any time. Some other applications of the microcomputer to low-temperature research are also described.

A microprocessor controller for a nuclear demagnetization refrigerator

J.P. Eisenstein, G.W. Swift and R.E. Packard

For the past six years microprocessor systems have been coming into use in research laboratories, but they have not yet gained the general acceptance that one might have expected. We would like to describe the use of a microcomputer system which has already been a great help to us. This paper has been prepared to answer numerous queries about our system and to encourage other laboratories to use microprocessor technology.

Our direct goal was to operate an ultra-low temperature facility (a nuclear demagnetization refrigerator) with a staff of only one or two people. Such a facility is usually operated 24 hours a day for at least a month at a time. The job of the microprocessor is to handle most routine tasks automatically and thus allow the experimentalist to concentrate on the more interesting aspects of the experiment. Such automation in the past would usually have been handled by hardwired electronics, probably a combination of digital and analogue systems. Analogue methods for such tasks as timing and data acquisition are rapidly disappearing in favour of digital techniques. The microprocessor is a device which permits these digital processes to be handled in software rather than hardware. This gives the advantage of saving the cost of the hardware construction and, if one is facile with the software, the development is considerably faster and the instrument more versatile.

We wish to emphasize that the greatest advantages of the processor are obtained only after the user has become sufficiently familar with the software instruction set. Although the first project might be completed faster and more cheaply using hardware, by the second or third the advantages of the processor become evident.

This paper is organized into two parts. The first deals with our primary application of the microcomputer, the automation of the nuclear demagnetization process itself. The second part briefly describes the use of the microcomputer in some other aspects of our low temperature research.

Nuclear demagnetization

Our nuclear refrigerator is of conventional design.[1] A dilution refrigerator is connected via a zinc heat switch to about 25 moles of copper nuclear refrigerant in the axial bore of an 8T superconducting solenoid. The magnet is energized by a voltage-programmable current supply and subsequently run in the persistent mode by closing a superconducting persistent current switch and turning off the current supply. A silver heat exchanger containing liquid He^3 is welded to the nuclear stage. This liquid is the experimental system of interest and contains a Pt^{195} NMR thermometer and various experiments.

Fig. 1 shows a typical operations schedule involving the current in the demagnetization solenoid. To start, the solenoid is fully energized and then put in persistent mode for a precool period lasting ~ 10 hours. During this time, heat flows from the nuclear stage to the dilution refrigerator through the closed heat switch. After the nuclear stage has cooled to the desired temperature (~19 mK), the heat and persistent switch open and the magnetic field is lowered at a constant rate which changes at t_4. When the final field is reached, the solenoid is again put into persistent mode. This completes the demagnetization, leaving the He^3 at some low temperature (our minimum temperature is 0.48 mK). Subsequent to the end of the demagnetization, the current may be ramped up or down to allow taking data at various temperatures. This is made possible by the fast relaxation time of the He^3 to the nuclear stage (about 3 min at 1 mK), as well as the low external heat leak to the nuclear stage (about 2 nW).

One of our earliest concerns had been whether the computer would create electrical interference which would cause undesirable heating in the refrigerator. The overall heat leak to the demagnetization stage proved to be independent of the running state of the computer, provided that most cables to and from the computer are shielded. However, our carbon resistance thermometers at the lowest temperatures show appreciable warming when the computer is operated. This is not a serious problem since these thermometers are not used below 20 mK. We have not yet investigated the operation of SQUID devices in the computer's environment. Computer rf noise may require these sensitive devices to be specially shielded.

Fig. 2 is a block diagram of our automated system. The heart of the system is a microcomputer[2] based on the Intel 8080 microprocessor. The computer itself contains a wide variety of peripheral devices used by the 8080 processor including random-access memory, parallel input/output ports, serial input/output for communications with a CRT terminal or teletype, a priority system for handling interrupts, and others.

To control the current in the main solenoid we employ a voltage-programmable current supply and control it with a

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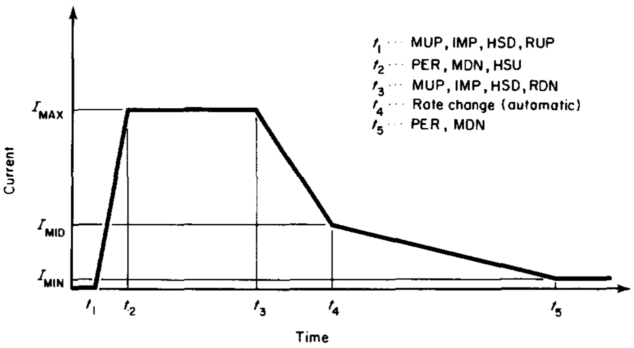

Fig. 1 A typical current vs time schedule for the operation of the main solenoid. The inset lists the various computer operations performed, the mnemonics being explained in Table 1

16-bit digital-to-analogue converter.[3] Thus the current ramp consists of up to 6.5 x 10^4 steps. The computer changes the 16-bit word according to a schedule determined by software from the user's original input.

If the computer's only task had been to perform the sequential timing involved in ramping the magnet, we might have employed timing based on the 8080 instruction cycle. This is both unwieldy and imprecise, but more importantly would use all of the processor's time. Since one generally would like to perform other computer tasks simultaneously with demagnetization, we use programmable interval timers[4] which employ a separate clock and interact with the processor via an interrupt line and a parallel output port. The computer is only busy with ramping during the short interval of time when the interval timer transmits an interrupt, signalling both the updating of the current in the solenoid (via the D-A converter) and the resetting of the interval timer. As the processor itself has only one interrupt line the computer employs a priority system to allow handling several interrupts simultaneously. Many of our programs, in addition to the demagnetization software, are interrupt oriented.

At certain times during the demagnetization, tasks must be performed which require a single bit of information, such as turning on or off the heat or persistent current switch. For such jobs we employ a home-built device dubbed the 'Bit-Box'. This device serves as a general-purpose computer-controlled switch-box. It consists of 32 one-bit latches controlling TTL drives, FET switches, mercury wetted relays, 115 V, AC switches, audio signals, and LED's. The computer outputs an 8-bit word to the device which determines which latch should be set and the sense of setting (ie, on or off).

The software for demagnetization is named DEMAG and has been developed over the past 3 years. It has been used extensively in the last year and is proving to be quite satisfactory. It and other commonly used programs are stored on programmable read-only memory and are thus not subject to accidental erasure.

The computer contains a resident monitor and assembler. The monitor contains several general-purpose subroutines; for example, the input-output routines for the CRT terminal. DEMAG uses this operating system, but in a marginal way. DEMAG could easily be made independent of any operating system.

There are two basic modes of operating DEMAG available to the user: manual and automatic. In either case the user starts by supplying the parameters of the process as shown in Fig. 1. These include the various currents and time intervals in decimal amperes and hours respectively. The pre-cool time, $t_3 - t_2$, is supplied only in automatic mode. In automatic mode the entire process is run by the computer with no need of user intervention, while in manual, all steps are initiated by the user from the CRT terminal. In the inset to Fig. 1 a table summarizes the operations usually performed at the various milestones in the demagnetization process. In either case the user maintains complete control over the process and may alter it at any time. This is accomplished by having the DEMAG software responsive to a series of 17 commands, shown on Table 1. Since the ramping is done by interrupts to the processor, DEMAG can remain responsive to user input while the ramps are proceeding. These commands give the user the ability to monitor and modify, if need be, the progress of the demagnetization. Furthermore, the user may in the middle of demagnetization return to the computer's operating system and perform other software-related jobs, some of which will be explained below

We feel that the capability embodied in the commands of Table 1 provides a useful guide for any DEMAG-type program. The software has two basic strengths. First is the fact that no human presence is needed during the 10 to

Table 1. DEMAG commands

Mnemonic	Function
IMP, PER	Make persistent current switch impersistent or persistent
HSU, HSD	Turn on or off the heat switch
MUP, MDN	Turns on or off current supply
RUP, RDN	Initiates magnetization or demagnetization
HLT, RST	Halts or restarts ramping
DIS, ENA	Disables or enables 8080 interrupt structure
CUR	Informs user of current current
CHR	Allows user to alter ramping rates
CHS	Changes sign of ramp
CHC	Allows user to abruptly change current
ESC	Escape from DEMAG into system monitor

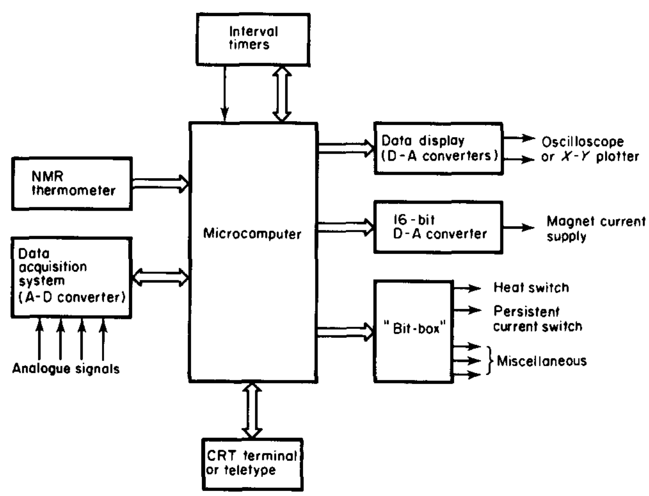

Fig. 2 Block diagram of automated system

20 hour demagnetization sequence. Second is the relative ease with which the program may be modified to suit future needs.

Other applications

The microcomputer can also serve as a data acquisition system in addition to performing control functions like demagnetization. Both analogue and digital data may be read and stored by the processor. While the digital data may be input directly in parallel binary form, analogue signals must first be converted to digital numbers. For this we employ a home-built device centred around a commercial 12-bit analogue-digital converter[5] of up to eight software-selected channels.

An example of the use of this data collection system is in a recent measurement[6] of the viscosity of normal liquid He^3 down to 1.5 mK. The viscosity was determined by observing the relaxation of liquid levels in two small reservoirs coupled by a tube of small cross-sectional area. As the relaxation took place (in times as large as 4.5×10^3 s) the liquid level was measured using a capacitance bridge whose output went to the data acquisition system. Hence a digitized record of the relaxation was stored for future processing. Before and after each relaxation the computer recorded several digital signals from the NMR thermometer.

The NMR thermometer is built according to the principles described by Aalto[7] and measured temperature by the Curie law dependence of the amplitude of a pulsed NMR signal in platinum powder. The system detects, integrates, and digitizes free-induction decay transients resulting from small initial tipping pulses ($\sim 5^\circ$). At temperatures above ~ 50 mK the signal to noise is small and the computer may perform simple signal averaging.

A second example of the computer's use is in a recent investigation of superflow in the B-phase of He^3. The apparatus is the same as for the viscosity measurement. Here the computer was used as a transient recorder and signal averager. Up to 100 superfluid flow transients at a given temperature were added together and then divided by computer. Furthermore, subsequent to the averaging, the results could be displayed on an oscilloscope screen or plotted on an X-Y recorder, using two 12 bit D-A converters.

Conclusion

We have briefly described how we have integrated a microcomputer into our ultra-low temperature facility. The total cost of this automated system was about \$7000, accumulated since 1975. Recent appearance of complete microcomputer systems could considerably reduce this cost. On the other hand, recent reductions in the price of minicomputer systems make these higher quality 16-bit machines more attractive than ever.

The microcomputer has allowed us to automate most routine control and data logging chores, resulting in the ability to run our low temperature facility with a smaller staff than usual. In addition, data recording is considerably more complete than could be achieved by manual methods. Beyond simple control and data acquisition functions, we have recently added a BASIC interpreter to give the computer analytic capability.

The authors are pleased to acknowledge both Mr J. Wallace and Mr J. Davis for contributing many ideas and construction aid in our development of this system. Professor T.M. Sanders helped launch the effort leading to this system and supervised the earliest assembly.

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4 Intel 8253
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