

THE DESIGN OF AN ULTRASOUND FIXED ARRAY
CONTROLLER FOR USE IN HYPERTHERMIA

BY

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THESIS

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CHAPTER I

INTRODUCTION

1.1. Local Hyperthermia

Hyperthermia, or the application of heat to a body, is used to produce temperature elevations in cancerous tumors. Temperatures above 42.5°C appear to retard the growth of tumors. However, hyperthermia alone is not usually an effective cancer treatment, but it has been shown to enhance the effects of radiotherapy and may be used in conjunction with chemotherapy [Meyer, 1984]. Localized hyperthermia involves the controlled delivery of heat to a restricted area of the body. The temperatures within the target region are monitored and maintained within desired therapeutic ranges determined by the nature of the normal and cancerous tissues in the treatment field. Uniformity of the temperature distribution is known to improve the therapeutic response. Temperatures in the range $42.5 - 45^{\circ}\text{C}$ are often employed during local hyperthermia. Since tumor tissue grows more rapidly at temperatures (41°C) which are only mildly elevated, a lower temperature bound exists for its treatment, and is an important factor. In addition, an upper bound also exists because care must be taken to minimize the destruction or alteration of normal healthy tissue within the heated region.

Hyperthermia may be viewed in a clinical setting, but controlled heating is also relevant to experimental research. Tissue response to heat, biological thermal modeling, and thermal dosimetry are a few areas of investigation which could benefit

from the development of a laboratory hyperthermia system. These experimental systems can be used in studies to improve the quality, safety, and reliability of the clinical systems.

Localized hyperthermia may be produced by several physical means, including ultrasound absorption, microwave irradiation, radio frequency current field induction, and other regional power deposition methods. Each technique has its own unique features and most suitable applications. The research and development described in this thesis involve ultrasound hyperthermia.

1.2. Ultrasound Hyperthermia

Ultrasound has several advantages for clinical application. It is a noninvasive mode, requiring no mechanical probing into the body. It is noninteractive with thermometry devices. No electromagnetic shielding is required. Another feature is that tumors absorb ultrasound better than normal tissue, as compared with electromagnetic energy.

Periodic vibrations due to passage of ultrasound waves through tissues cause displacement of the tissue molecules. Heating is produced as a result of the absorption of the ultrasonic energy in the tissue [Cheung and Neyzari, 1984]. Ultrasound propagation is relatively slow in tissue (approximately 1.5×10^5 cm/sec at a 1 MHz), resulting in short wavelengths (0.15 cm at 1 MHz). The waves propagate through the body with little reflection, as long as the acoustical impedance remains continuous. Ultrasonic impedance depends on the product of density and propagation velocity. These tissue properties remain fairly constant throughout the body with two major exceptions.

These are bone and air. Interfaces between bone (or air) and tissue result in unwanted reflections. As a consequence, ultrasound hyperthermia is not recommended for bone-containing regions, or for those with air (e.g., lungs, abdomen). Furthermore, a tissue-equivalent bolus filled with degassed water may be required to couple the patient's surface tissue (i.e., skin) to the ultrasound applicator, thus avoiding excessive reflection.

There are two basic tumor geometries to consider in local hyperthermia therapy. They are the surface tumor and the deep-seated tumor. Each has its own qualitative desired temperature (intensity) distribution pattern (Fig. 1). (Figures appear on page 35.) Deep-seated tumors require beam focusing while surface tumors do not.

For beam focusing, the short ultrasonic wavelength allows the use of a moderately sized focusing lens to achieve heating with reasonable intensity over a small area at a given depth. More recently, focusing by constructive interference was achieved by digitally phasing each transducer of a multielement applicator [Benkeser, 1983; Ocheltree, 1984]. The focused beam may then be electronically steered to various locations and depths by a phased array controller [Silverman, 1984], where depth is varied by frequency selection.

Full attention may now be turned to surface tumors and unfocused ultrasound beams. Examination of Fig. 2 reveals the frequency dependence of heating depth. The concept of depth here is better appreciated with a basic understanding of heating by plane wave energy.

From Fig. 2 one can qualitatively observe how appropriate the heating pattern is for surface tumors as most of the power is absorbed at shallow (tumor tissue) depths. The deeper (normal) tissues are less affected, except possibly at the tissue boundary.

The intensity (W/cm^2) of a plane wave decreases exponentially with penetration depth, according to the attenuation constant α (cm^{-1}). The effective heating depth d is inversely proportional to this constant as $\alpha d = -\ln(1-k)$, for all k , where

$$k = \frac{\text{Power absorbed between 0 and } d}{\text{Total power incident at } x = 0}$$

Furthermore, the attenuation coefficient increases linearly with frequency, resulting in a reciprocal relationship between depth and frequency. The frequency should be chosen to provide adequate heating in the tumor tissue and yet provide great enough absorption (high α) for adequate heating with minimal power, so that heating of normal tissue below the tumor is minimized. In order to avoid the problem of excessive surface heating, the coupling bolus may have cold water circulated through it.

1.3. Ultrasound Applicator

Ultrasound is generated from electrical power by a piezoelectric transducer. Cross-cut, nonconducting crystals, activated by high frequency voltage, produce pressure waves that can heat tissue. Thus, an electrical waveform of appropriate frequency content might be faithfully replicated by an ultrasonic one. Typically, a single sinusoid of a few megahertz is applied.

The transducers used in ultrasound hyperthermia produce a

beam of finite effective width or diameter (Fig. 3). Intensity decreases continuously, but rather sharply, in an outward radial direction within a plane which is perpendicular to the beam.

Ultrasound applicators often consist of multiple transducer arrays. The elements are fixed in some geometrical pattern, often within a plane parallel to the heated surface. For phased (focused) arrays, proper transducer spacing is crucial to proper beam construction.

For the fixed (unfocused) array which is used to heat surface tumors, spacing is determined by the effective beam width. Proper spacing should insure proper beam superposition in an attempt to provide a continuous and constant intensity field within any parallel plane. This should produce the desired temperature uniformity.

Multiple transducer applicators are necessary for large treatment fields since a single element has finite beamwidth and can only transmit a limited amount of power. Transducers also become nonlinear above a certain power level. At reasonable levels, the efficiencies of transducers should remain constant and equal to each other, allowing acoustical power output control by electrical input power control. Well-spaced multiple transducer arrays which have the intensity of each element individually controlled may be capable of producing desired temperature distributions in a plane (or volume) as a function of time. The design and construction of an ultrasonic applicator controller are described in this thesis.

Mechanical movement or translocation of the applicator may be useful for ultrasound hyperthermia. The simplest task for a

translocator would be position control prior to or during treatment. This could be used to maintain precisely localized heat delivery. However, a more sophisticated translocator (e.g., a step motor control system) may be used to scan over a prescribed (possibly 3-dimensional) treatment field. Greater uniformity of temperature distribution may be achieved this way, decreasing the risk of overheating in any one place. Applicator translocation, along with individual element intensity control, should provide good flexibility in the controlled application of unfocused ultrasound to surface tumors for localized hyperthermia.

1.4 Controlled Ultrasound Hyperthermia System

Clinical delivery of ultrasound hyperthermia in a safe, effective manner might be realized by the closed-loop system whose block diagram appears as Fig. 4.

Controlled excitation signals for the transducers are generated by the microcomputer-based applicator array controller. They are modified and amplified by radio-frequency amplifiers (one per element) which require a large power supply. As the ultrasound is applied, the array might be translocated. During treatment, thermocouple probes at known locations, within the treatment field produce electrical signals which are interpreted and processed by the multichannel thermometry system. This microcomputer-based sub-system is available for communication of temperature data to the central computer (Central) when requested. Central uses this feedback to dynamically control the array intensity pattern via the array applicator controller sub-system.

The calculations for dynamical control are complex,

time-consuming, and require a multitude of additional information regarding biological thermal modeling and thermal dosimetry, as well as current information on the nature and geometry of the treatment field. All the while, the central computer must also serve as a system controller in a non-dynamical sense as it monitors and interacts with all types of peripherals in a timely fashion.

A form of the previously described system is being constructed at the University of Illinois for experimental research and also serves as a prototype for a proposed commercial clinical system (SONOTHERM 1000) to be manufactured by URI Therm-X in Champaign, IL. Heating experiments are being performed on tissues which are subjected to various conditions for temperature data acquisition. Later, tests might involve in vivo testing of mammalian organ responses. These results may lead to breakthroughs in the areas of thermal modeling and thermal dosimetry which, in turn, might enable the system loop to be closed effectively. Throughout the experiments, information regarding system and component performance will naturally be accumulated as well.

System specifications for the prototype are made in the remainder of this chapter. It is realized that such a prototype is subject to modification in future systems.

The transducers are channel 5400 ceramic and are defined by scratching the positive electrode plating. Sixteen elements are arranged in a four-by-four fixed unfocused array with an area of 231.0 cm^2 (36 sq. in.). Each element is operable at 150 W or more for an intensity of 10.4 W/cm^2 at the source. The power

requirement for all 16 elements might be met at 230 VAC, 24 A. A frequency of 1 MHz is common, with such an intermediate value rendering an effective heating depth of about 3 - 4 cm.

Each RF amplifier should have a bandwidth of 0.5 - 3.0 MHz or wider, and along with its transducer, should have an identical power efficiency of about 0.75. The RF amps should accomplish more than amplification and regulation. Filtering is required and coaxial transmission line effects might have to be compensated for.

A 16-channel thermocouple (copper-constantan) thermometry system (TX-100) can communicate temperature data to the central computer over an RS-232C standard line. This microcomputer-based subsystem performs calibration and is well-tested [Ozarka, 1984].

The central host computer is an Apple IIe which might perform temperature data acquisition as it controls heating. The clinical version may be a DEC Micro PDP-11.

The applicator microcontroller for the fixed array is based on the Intel 8031 microprocessor. It generates digital RF signals and also modulates them for element intensity control. The microprocessor performs array actuation as it receives commands from the central computer over RS-232C and executes them. This device was built and tested. Its design and operation are described in the remainder of this thesis.

CHAPTER 2

FUNCTIONAL HARDWARE DESCRIPTION

2.1. Overview

The ultrasound fixed array controller is really an actuator in the system as it receives command character strings and interprets them to produce the appropriate initial form of the excitation signal for each transducer. This is accomplished as the microcomputer is programmed for its serial communications protocol with the central computer and for configuration with peripheral hardware devices. The hardware description in this chapter provides a functional understanding of the operation of the controller. This system generates radio-frequency signals and performs duty cycle modulation on them.

2.2. Microcomputer

The Intel 8031 microcomputer is a single-chip processor which serves as the heart of the controller [Intel, 1981]. It is equivalent to an Intel 8051 without the ROM. Thus, it must access an external program memory while it contains 256 bytes of on-chip RAM. The Intel 8031 has two programmable timer/counters which are utilized in addition to its programmable receive-buffered full-duplex serial port. Serial and timer interrupts are utilized and prioritized as well. There are also thirty-two bidirectional I/O pins for individual or parallel use.

The Intel 8031 is transistor-transistor-logic (TTL) compatible and is used with other digital devices [Texas Instruments, 1981]. The nature and purpose of each hardware

interaction are stated and described in the following sections.

The Intel 8031 has an on-chip oscillator circuit so that only an external crystal is required. The chosen 6 MHz crystal results in a program instruction cycle lasting two microseconds [Intel, 1982a]. The crystal output also clocks each timer/counter, where one of these is used to maintain the serial communications rate (baud). Perhaps the most prominent role here of the oscillator output signal is that of being the radio-frequency source for the excitation of the ultrasound transducers.

An Intel 2716 (2 K x 8) EPROM contains the program for the Intel 8031. The instruction code burned therein is accessed by the Intel 8031 central processing unit in a timely fashion, via a LS74N373 latch (Fig. 5). Note that port 0 and some pins of port 2 are active during this continuous process. The Intel 2716 has a maximum access time of 450 nanoseconds which places an upper bound upon crystal frequency section [Intel, 1982b].

The Intel 8031 serial port has separate pins (and registers) for transmission and reception. It is software programmable as an eight-bit or nine-bit UART with variable baud rates. This asynchronous communication mode can operate over an RS-232C link to the central computer. This requires translation between the logical lows and highs of TTL (0-5v) and those of RS232 ($\pm 12v$). Translator chips from Motorola are used for transmission (MC1488) and reception (MC1489).

2.3. Radio-frequency Signal Generation

The radio-frequency source for all sixteen elements conveniently originates at the oscillator output (pin 18) of the

Intel 8031, so that an oscillator circuit need not be built. This TTL square wave has a duty cycle of about 23%. However, the desired RF square wave has a 50% duty cycle so that a sine wave approximation will result from band-pass filtering it. This wave can then excite the transducers near a single desired frequency. All of this implies the necessity of at least one frequency division, so that the highest possible excitation frequency is half the crystal frequency.

The circuit shown in Fig. 6 produces outputs of 1 MHz and 3 MHz by dividing 6 MHz by six and two, respectively, with an LS74N92. These are desirable frequencies for ultrasound heating tests. Frequency selection is made with a single-pole double-throw switch. A buffer chip (LS74N07) is required (with pull-up resistors) to provide sufficient current in expanding from one to sixteen channels. Each of four LS74N07 outputs can drive four more inputs.

Once the RF signals are available for element excitation, the power delivered to each transducer must be individually controlled. This is done electronically by duty cycle modulation, where it is assumed that power is proportional to the fraction of time the excitation signal is applied. The duty cycle signal for each element at a given time is determined by the processor.

2.4. Duty-Cycling

Parallel output of sixteen bits for intensity control is not as simple as expected, because sixteen I/O pins are not available simultaneously. Port 3 performs alternate special functions for the processor [Intel, 1982c] and ports 0 and 2 are occupied with

program instruction fetching. The problem is alleviated by using two octal latches (LS74N373) and writing to eight-bit port 1 twice in succession, once per latch. After each write, the proper latch is enabled and disabled by the processor from one of two other I/O pins. The delay between the two latching is very small and therefore inconsequential.

Duty cycle modulation of each RF signal is achieved with hardware by logically combining it with its duty cycle signal, which varies much less frequently. Each gated signal is then sent to an RF amplifier over its own 50-ohm transmission line, necessitating the use of line drivers. Fortunately 50-ohm line drivers (LS74N128) are available with NOR logic so that gating and driving are accomplished with the same device. Logic duality implies proper output from the drivers if active low inputs are applied to them.

2.5. Miscellaneous

All of the described hardware was wire-wrapped with DIP sockets on the Vector 3682 card (9" x 4.5") which plugs into a TRW cinch connector. It draws less than 1 ampere from a plus-and-minus 12 V DC power supply with a 5 V regulator. After powering up, the controller is activated by setting the reset pin high, then low, in order to initiate program execution and command anticipation.

CHAPTER 3

SOFTWARE DESCRIPTION

3.1. Overview

The microcontroller is programmed to maintain its serial communications protocol with the central computer (Central) in order to activate the array and control the intensity output from each of the transducer elements. While the software is perhaps best characterized by the character strings it receives and the commands it executes as part of the protocol, consideration is also given to the determination of the intensity bits whose variations constitute the preexcitation signals for the array. This chapter explains the structure and content of the software as the functions of each program section are described.

The Intel 8051 assembly level program is called DUTY and a documented version of it appears in Appendix A. DUTY consists of three routines which are simply named MAIN, SERINT, and TIMINT. Program execution is initiated in MAIN. SERINT is the serial interrupt routine which is called upon completion of a character frame reception or transmission. It is configured in MAIN along with TIMINT, which is a timer interrupt routine. TIMINT has the higher interrupt priority of the two routines but it is enabled and disabled from within SERINT. Before proceeding further with a description of each routine, the serial communication protocol requires discussion.

3.2. Serial Communication Protocol

To help insure safe and controlled delivery of hyperthermia,

a set of rules must be established which govern the exchange of information between the array controller and Central. This protocol is necessary to provide synchronization, error detection, and mutual status monitoring between the two devices.

Communication is based upon a command-reply format which is initiated by Central. Commands are sent as ASCII character strings which may be only one or two characters long. A single-character reply is made after successful reception of the last character of a valid command string. But if an error is detected by the controller, the entire command string is ignored and a reply character immediately indicates the nature of the error. Furthermore, the array is turned off and an error flag is set so that the controller must receive a software restart command before it will recognize and execute any other commands. In any event, Central should wait for the reply before it issues another command.

One type of communication error results from a violation of the command structure. Every command string consists of at least one letter character which may or may not be followed by one or more number characters. The number characters are of the pseudo-hex form [Silverman, 1984] where the numerical value to be used is that of the lower nibble of the seven-bit ASCII-encoded byte. The high (three-bit) nibble of a valid pseudo-hex number character has a value of three. The distinction between a hexadecimal value and its pseudo-hex character representation is significant.

hex value	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
pseudo-hex	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?

The controller anticipates a command as it awaits the reception of a letter character which it may recognize as the first character of a known, valid command string. If no such recognition takes place, an invalid command error occurs.

For those commands which require number characters (data) after the letter, a number flag is set after letter character reception. This flag is not cleared until after the last number character is received, at which time the data are processed and a reply is given to Central. When the flag is set, an invalid data error occurs if any character is received whose high nibble is not three (e.g., a letter character). The only exception to this rule is the single-character restart command, which is always accepted and executed.

An error condition results from incorrect parity which may occur if the proper ASCII character byte is somehow altered as its bit signals propagate over the RS-232C line and are clocked through serial port shift registers. The microcontroller performs the parity checks and informs Central only if there is a problem.

Most of the protocol involves initiation by Central in order to achieve successful transmission, reception, and interpretation of the command character strings. This is not necessarily the case, however, where mutual device status monitoring is concerned. This part of the protocol is necessary in the event that one of the devices should malfunction or if there is a communication problem of some sort.

If the controller does not receive a character within approximately ten seconds, it initiates communication by sending a warning character. If Central does not send a character within one more second, the controller assumes that there is a system problem and promptly shuts off the array to avoid excess or uncontrolled heating. Another character is sent to indicate a crash as the error flag is set.

This automatic shut-down feature is necessary for safe system operation. A possible shortcoming of this feature is that Central must periodically send a valid dummy character to the controller. The necessity of doing this may affect overall system performance. A version of DUTY without automatic shut-down has been made available for laboratory use.

Another responsibility of Central is to note if it is receiving several consecutive error replies (or no replies) from the controller, so that the system operator may be instructed to make sure that the array has indeed been turned off.

3.3. Main Program - MAIN

The actual main program is very short and would be trivial if it were not delegated the task of performing the automatic shut-down feature of the protocol. This feature is implemented in MAIN since both timers of the Intel 8031 are used for other purposes. The ten-second and one-second delays are realized consistently by the routine whether the array is heating or not. There was once a small problem regarding consistency because during heating, MAIN is periodically interrupted for a short but considerable duration. This duration has since been accounted for

by using a separate set of delay reload parameters during heating.

In either case, if one of the delay "clocks" runs out, a warning flag indicates which one and whether to warn Central or crash into an error condition (Figure 7).

Before the delay routine is entered into and serial interrupt anticipation begins, instructions must be executed to perform all necessary initializations. The array is shut off and variables are assigned initial values. The two timer interrupts to be used are prioritized. The serial interrupt is enabled after the serial port is configured with a timer whose reload value determines the baud. The other timer is also configured in the reload mode for its role with the timer interrupt routine.

MAIN also contains two short subroutines which may be called from SERINT as well. One of these (OFF) shuts off the array and disables the timer interrupt. The other one (TRANS) insures completion of a previous serial transmission before attempting another, thus avoiding overwrite.

3.4. Serial Interrupt Routine--SERINT

The majority of the software is contained in SERINT. This routine is executed nontrivially after each character frame reception. The routine examines the character's validity and type for command string interpretation as part of the protocol (Figure 8). Successful character examination and recognition are followed by a branch to the appropriate program location where the command is executed and from which a character reply is sent to let Central know that all is well.

A list of the commands appears in Table 1. (Tables appear on

page 30.) All commands begin with a letter. Those commands which contain no numbers are immediately executed. Those which require numbers postpone the execution and do not reply until the last number character is successfully processed. A pseudo-hex character is represented by an 'n' in the table.

Each command may be considered as one of four functional types: transducer selection, intensity level settings, array activation, and display.

The D command is used to determine which of the transducers may be excited. It provides a form of on-off control. This makes the system safer by insuring that an unneeded transducer will remain off even if it has a non-zero intensity level assigned to it.

The four numbers which succeed the D have their lower nibbles concatenated into a sixteen-bit on-off byte which occupies two registers. The transducer number corresponds to bit number (ranging from 0 to 15) and location. Bit three of the first received number character is for element fifteen. Bit zero of the fourth and last number in the string is for element zero.

One set of commands (A, I, J, K, L, M) is used to set the transducer intensity levels between zero and one hundred percent in ten percent increments. Some of these six commands must be used combinatorially in order to assign different specific levels for each of the transducers. Three commands (I, L, M) are unique in that they reply with a number character (pseudo-hex between 0 and :) whose value (between 0 and 10) is the current intensity level of a transducer.

Another set of commands (B, N, R, S) is used to operate the array. Once the desired initial intensity levels are set, the B command enables the timer interrupt routine to excite the array as it performs duty cycle modulation according to such levels. During heating, commands may be received and executed to change the levels without affecting the performance of the timer routine. The S command calls OFF to stop heating by disabling the timer routine.

The R command executes a software restart similar to a hardware reset. First, the array is shut off. Then, a known program code address near the beginning of MAIN is pushed onto the stack so that execution resumes there after returning from the interrupt. At that point, the stack is cleared and variables are reinitialized. The intensity levels remain the same since RAM is unaffected.

The N command performs no operation other than a reply to Central. This is the command which would be periodically sent by Central to avoid automatic shut-down of the array.

Finally, the H command requests a display of the intensity levels of each element being used. The reply consists of twenty-six ASCII characters which produce a four-by-four character grid on a terminal screen. The upper-left character indicates the status of element fifteen. The lower-right one is for element zero. An asterisk indicates an element which is not being used. A number indicates the intensity level of an element in use. Note that ':' means ten.

A list of replies appears in Table 2. Successful command

execution usually calls for a C reply, but the exception to this rule has already been cited.

The X reply may only result from an A command. It indicates neither successful command execution nor the existence of an error condition. Central should simply repeat the A command with a number whose value is within the allowed range.

Two entries in the reply table are characters which are sent to Central as part of the automatic shut-down feature of the protocol. These are pseudo-replies because they are initiated by the lack of a command.

Rounding out the table are the character replies which indicate the existence and nature of a protocol error as previously discussed in this chapter.

3.5. Timer Interrupt Routine--TIMINT

TIMINT is a short routine which provides the mechanism for duty cycle modulation of the preexcitation signals. This software is placed within a high priority interrupt routine because interruption of its execution would ruin the timing of the duty cycle.

Duty cycle modulation is achieved by "slicing" up a time interval into ten equal parts. Each slice duration equals the time between timer interrupts. The slices are numbered from one to ten. A utilized transducer with an assigned intensity level of n will be left on during the first n slices and off during the last $(10-n)$ slices. TIMINT uses a register to keep track of the current slice number each time it is called. The slice number is updated after each execution.

During execution, TIMINT decides which bits should be left on for the next slice interval. Every element's slice value (intensity level) is compared with the current slice number. If the former exceeds the latter, a duty cycle bit is set for that element. A sixteen bit duty cycle byte is stored in two registers in the same manner that the on-off bits are stored. Each of the two register contents results from eight comparisons which are separated from each other by a rotation through carry in order to properly position each bit within a duty cycle register.

Finally, the duty cycle bits are logically combined with the on-off bits to avoid excitation of the transducers which are not supposed to be used. The resulting sixteen intensity bits are then ready to be latched out through port 1 at the beginning of the next timer interrupt.

The timer whose overflow activates interrupt is configured in a programmable reload mode. The smallest reload value was chosen so that the duration between each interrupt would be long relative to the execution time of the routine. This leaves time for completion of command execution by SERINT during heating. Such completion prevents both excessive stack growth and the possibility of overwrite occurring in the serial reception register.

The actual time between the timer interrupts is 0.512 msec. The routine is executed once for each of the ten segments of the duty cycle so that a full cycle lasts 5.120 msec. This order of magnitude in time should be small enough to make the resulting hyperthermic delivery seem continuous as thermal ripple effects are not noticeably incurred.

CHAPTER 4

INTERFACING TECHNIQUES

4.1. Overview

Two types of controller interfacing must be considered. The first one concerns the exchange of ASCII-encoded character data between the controller and either a terminal or a central computer. The other interface is with the radio-frequency amplifiers which modify the duty cycle of the array excitation signals.

4.2. Central Computer Interface

Serial data are sent asynchronously to the controller over an RS-232C line. The 25-pin female connector has only four of its pins utilized to configure the controller as a DTE (Data Terminal Equipment) device. This necessitates use of a null modem if a terminal is used to send commands. A computer, on the other hand, is usually a DCE (Data Communication Equipment) device.

Each character frame is ten bits long including one start bit and one stop bit. The remaining eight bits contain the seven-bit ASCII value of the character, with the highest bit (b7) reserved to produce even parity. Correct parity is required for both commands and replies.

The baud rate for the controller depends upon the crystal frequency and the reload value for the Intel 8031 serial port's associated timer. The baud rate is given by

$$\text{Baud Rate} = \frac{(\text{crystal frequency})/12}{(32) (256-\text{TH1})}$$

where TH1 is the reload value. The thirty-two in the expression is replaced by sixteen if a particular bit of register PCON is set [Intel, 1982a].

The controller currently operates at 300 baud. This value may be increased to 2400 without introducing error between the actual and desired values. The constraint is placed as a result of the discreteness of integral reload values.

An Apple IIe personal computer can be used as the Central computer. A parallel-serial-input-output (PSIO) card [Videx, 1982] has been installed in an Apple IIe and configured for asynchronous serial communication with the controller according to the given baud and data format (Appendix B). The PSIO card transmits parity but does not check it upon frame reception. This task should be performed in software.

An Applesoft BASIC program has been written and tested that implements the serial communication protocol with the controller. The program is called TRY1 and appears in Appendix C. This program must be executed in the deferred mode since it contains Apple DOS operating system commands along with the BASIC program statements. BASIC and DOS must be used together so that the Apple IIe memory can write to and read from the different peripherals in an orderly fashion which is consistent with the protocol.

The program TRY1 inputs a command string from the keyboard to memory and then prints it to the controller via the PSIO card. It then gets the reply, reads it into memory, and echoes it on the Apple IIe terminal screen.

Applesoft BASIC is slow and program execution might be unsatisfactory for protocol implementation at a very high baud

rate. Another feature of the language is that a carriage return--linefeed character sequence is often automatically appended to the command strings by virtue of the INPUT statement. The Intel 8031 program DUTY ignores these two characters to compensate for this quirk of the BASIC programming language.

4.3. Amplifier Interface

The radio-frequency amplifiers receive duty-cycled TTL square waves at their inputs and produce duty-cycled sinusoidal waves that are regulated at much larger amplitudes. A large gain is required for sufficient power delivery to each transducer. Regulation is particularly important since TTL highs are defined by voltage levels whose variation is widespread. Band-pass filters which have a fairly high Q (quality) are required to convert the square waves into sinusoidal approximations at the same frequency and with the same duty cycle.

Physically, the LS74N128 outputs are wired to female, 3/8 inch, floating ground BNC connections via the cinch connector. The signals then propagate over a 50-ohm transmission line (RG-58A cable) to the RF amps, where line termination for impedance matching accompanies the more prominent signal modification tasks.

CHAPTER 5

MEASUREMENT RESULTS

5.1. Timing Measurements

Most of the timing measurements were made on a Hewlett Packard Logic Analyzer (Model 1630D). The analyzer can sample digital signals during Intel 8031 program execution, store the samples, and display the signals as logical highs or lows along a time axis. The axis may be resolved into intervals as short as ten nanoseconds. The radio-frequency signals were measured first, with the primary clock source of 6 MHz having its frequency value immediately verified. The 1 MHz and 3 MHz square waves were then observed at their LS74N128 inputs. These signals were ON fifty percent of the time as required, and their frequencies were verified as well.

Duty cycle signals were measured next at their LS74N128 inputs. The experimental "percent time on" was computed for every intensity level and satisfactorily compared to the expected theoretical value (Table 3), demonstrating the success of TIMINT.

Complementary oscilloscope measurements were made for both the RF signals and the duty cycle signals. The oscilloscope was also used to observe duty-cycled RF signals for each intensity level at the LS74128 outputs.

5.2. AC Power Measurements

Power measurements were made which demonstrated that the power delivered by an AC signal is proportional to the fraction of time that the signal is turned on. The AC signals were produced by band-pass filtering the RF square wave at the end of a

transmission line.

Each of the RLC band-pass filters (Appendix D) uses a short 50-ohm resistor to match the line impedance and prevent "ringing" at the point of measurement. The value of L , given R , is determined by the desired Q . The value of C , given L , is dictated by the desired frequency passband location.

The filters emulate the RF amps which would normally be used. The filter outputs are approximately sinusoidal signals, each of whose frequency has been correctly verified on an oscilloscope. The sinusoids represent unamplified transducer excitation signals. The AC power measurement results for these signals may be used to infer similar results for the actual transducer input signals.

The AC power data were taken on an RMS voltmeter and the power level is taken as the square of the RMS voltage reading. The full power delivered to the 50-ohm load was only about 30 mW at each frequency. For each intensity level this value is divided by the full power level value to determine the experimental percent power delivered. The theoretical percent values agreed very closely with the duty cycle modulation of the RF signal at both frequencies. This is the most important result of this chapter.

CHAPTER 6

POSSIBILITIES FOR CONTROLLER ENHANCEMENT

The existing controller was built testing the prototype ultrasonic hyperthermia applicator. There are a variety of possible modifications and additions to the controller which may enhance its performance and flexibility of use. A few suggestions are listed below along with a brief explanatory description.

A different crystal value would decrease instruction cycle time. It would also allow operation at a higher maximum baud rate, especially if the proper bit of PCON is set. However, a faster EPROM may be necessary to accommodate for the faster crystal.

A higher frequency source (e.g., 12 MHz) might also lead to the use of a programmable counter (e.g., LS74N177) which may divide by any integer between two and seven. A new command would be introduced which would use I/O pins to select the divisor and choose the desired transducer excitation frequency. The heating depth would be varied in this manner.

Manual, continuous excitation frequency variation might be available if a function generator could be made TTL-compatible by proper adjustment of the amplitude of a square wave. This input would replace the SPDT switch at pin 3 of LS74N07 (Figure 6).

Greater flexibility of intensity control might be achieved by introducing more commands for this purpose. A good command might be a three-character sequence where the last two characters are numbers which indicate an intensity level and a transducer number. Another possible format is a letter followed by sixteen intensity

level numbers, where transducer number is related to character location within the string.

Further flexibility of control would be gained if overall power factors accompanied the existing relative factors [Silverman, 1984]. The maximum slice number would be the product of the maximum overall value and the maximum relative value. The two letter values need not be ten, but may well be increased as high as fifteen without creating any new problems. Note that a two-character command for overall power level would be required.

A control scheme might be employed which varies the phase of each duty cycle signal as well as its duration. Phasing would be achieved by updating individual slice numbers for each element instead of updating the same slice number for all. The command format for phasing would closely parallel that of the intensity level commands. It is not known whether phasing at such a low frequency has any useful application in producing a more uniform heating pattern.

An LED display could be installed to qualitatively indicate (by relative lamp brightness) the ultrasound intensity delivered by each element. The duty cycle signals at the latch outputs would have to be buffered to provide sufficient current for both the line drivers and the LED display.

A BASIC program could be written for user-friendly interaction with the Apple IIe for array control. The program would prompt the operator for information regarding element selection, intensity values, and array activation. This information would be translated into command character strings for the controller while the current intensity levels are monitored.

A modified form of TRY1 would function as a subprogram to maintain the protocol.

The interaction program might be used at the system level along with other programs for system status display and temperature data acquisition.

TABLES

Table 1
Command List

STRING (n = number character)	NAME and/or NAME and/or DESCRIPTION
Dnnnn	DECIDE which elements can be excited.
An	ASSIGN an intensity value of n to all elements.
In	INQUIRE about the current intensity value of element number n. The reply is a number character for the value.
Ln	LESS. The intensity value for element number n is decremented by one. Same reply as the I command.
Mn	MORE. The intensity value for element number n is incremented by one. Same reply as the I command.
J	Decrement the intensity value for every element by one.
K	Increment the intensity value for every element by one
B	BEGIN heating. Excite array.
S	STOP heating.
R	Software RESTART. Also stops heating.
N	NO OPERATION. Does nothing but reply.
H	Displays a grid of intensity values by sending twenty-six characters.

Table 2
Reply List

<u>CHARACTER</u>	<u>NAME and/or MEANING</u>
C	COMMAND EXECUTED successfully.
X	Data out of BOUNDS. This is not a true error condition.
U	WARN Central that a crash may occur shortly.
O	CRASH. Controller has shut off the array and entered an error condition.
Y	INVALID COMMAND letter. Error condition.
Q	INVALID DATA number. Error condition.
W	WRONG PARITY. Error conditions.

Table 3
Duty Cycle Timing Measurement Data

<u>THERORETICAL TIME ON (%)</u>	<u>ACTUAL TIME ON (%)</u>	<u>ACTUAL TIME N (%)</u>
0	0.00	0.000
10	0.51	9.961
20	1.02	19.922
30	1.54	30.078
40	2.04	39.883
50	2.56	50.000
60	3.06	59.765
70	3.58	69.922
80	4.09	79.296
90	4.61	90.039
100	5.12	100.000

Table 4
AC Power Measurement Data

THEORETICAL POWER (%)	V_{RMS}	V_{RMS}^2	ACTUAL POWER (%)
<u>f = 1 MHz</u>			
100	1.226	1.503	100.00
90	1.163	1.353	90.02
80	1.097	1.203	80.04
70	1.026	1.053	70.06
60	0.953	0.908	60.41
50	0.870	0.757	50.37
40	0.778	0.605	40.25
30	0.674	0.454	30.21
20	0.551	0.304	20.23
10	0.390	0.152	10.11
<u>f = 3 MHz</u>			
100	1.196	1.430	100.00
90	1.132	1.281	89.58
80	1.068	1.141	79.79
70	1.002	1.004	70.21
60	0.927	0.859	60.07
50	0.845	0.714	49.93
40	0.756	0.572	40.00
30	0.656	0.430	30.07
20	0.535	0.287	20.07
10	0.379	0.144	10.07

FIGURES

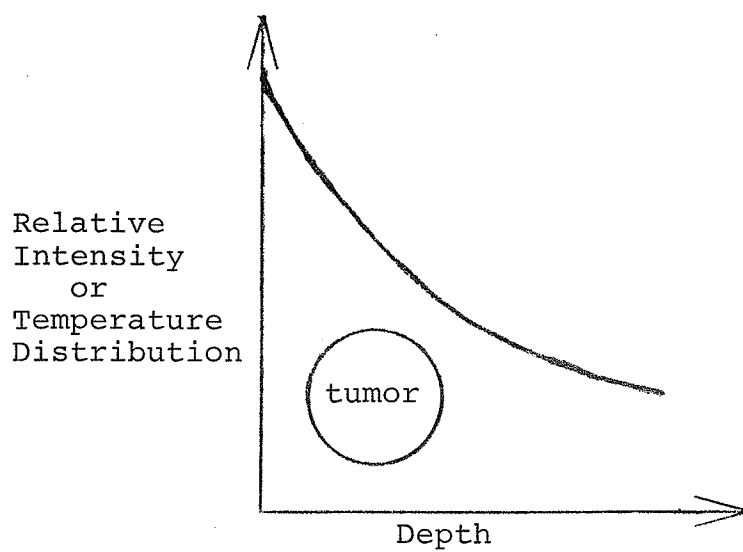


Figure 1a. Surface tumor with associated heating pattern.

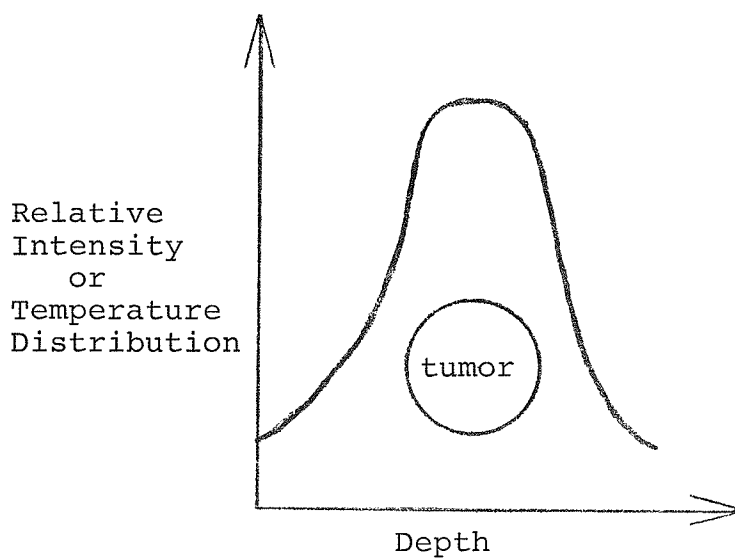


Figure 1b. Deep-seated tumor with associated heating pattern.

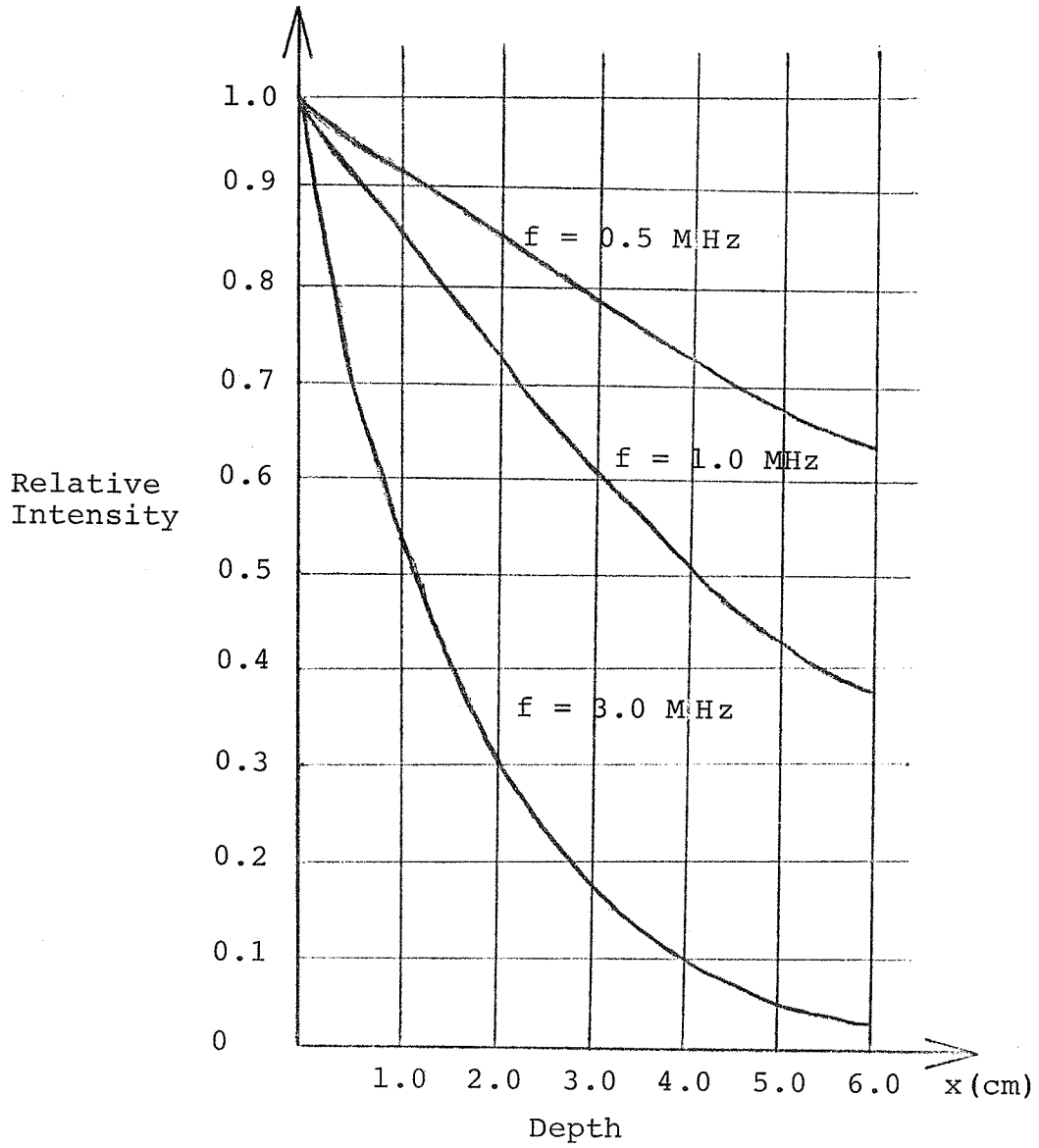


Figure 2. Frequency dependence of ultrasonic penetration depth in tissue.

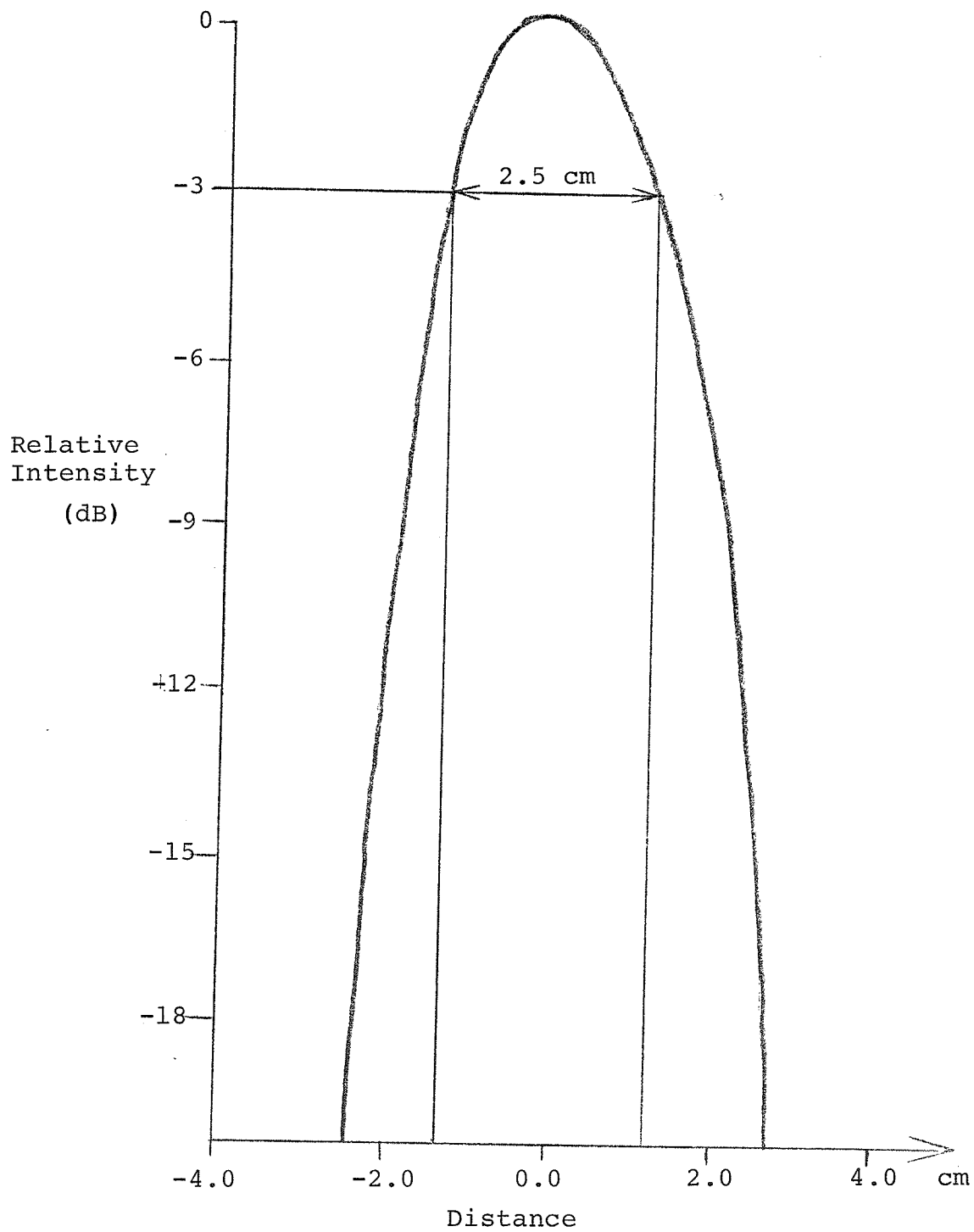


Figure 3. Ultrasonic intensity profile in a plane normal to the transducer.

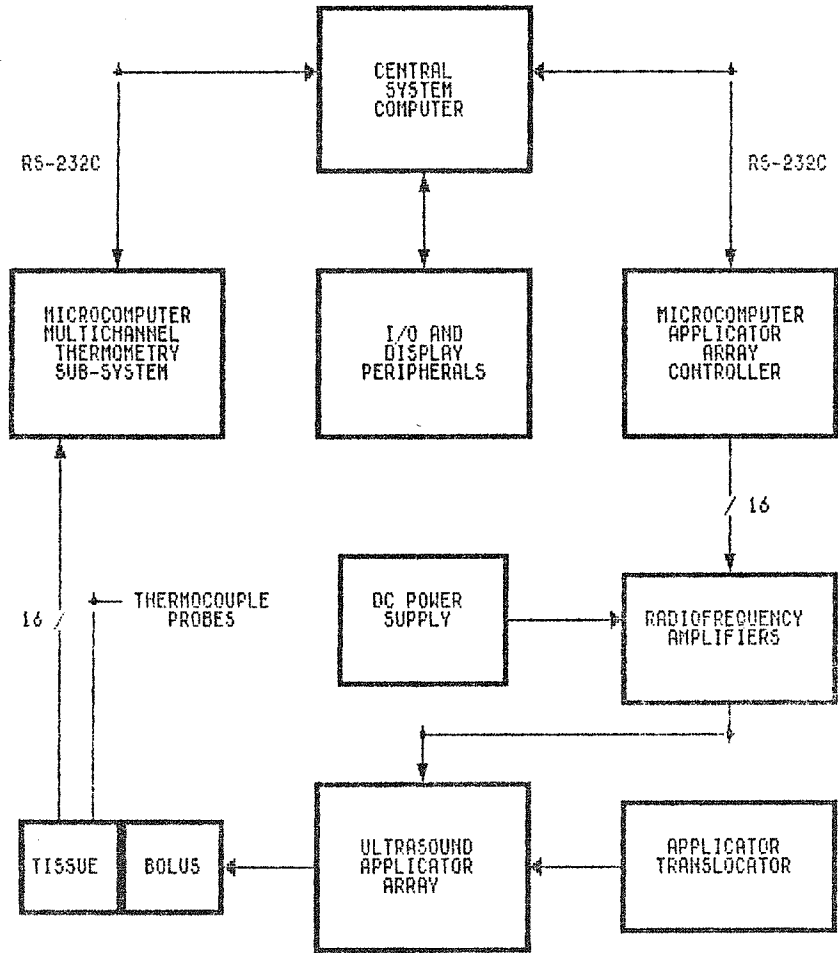


Figure 4. Ultrasound hyperthermia system.

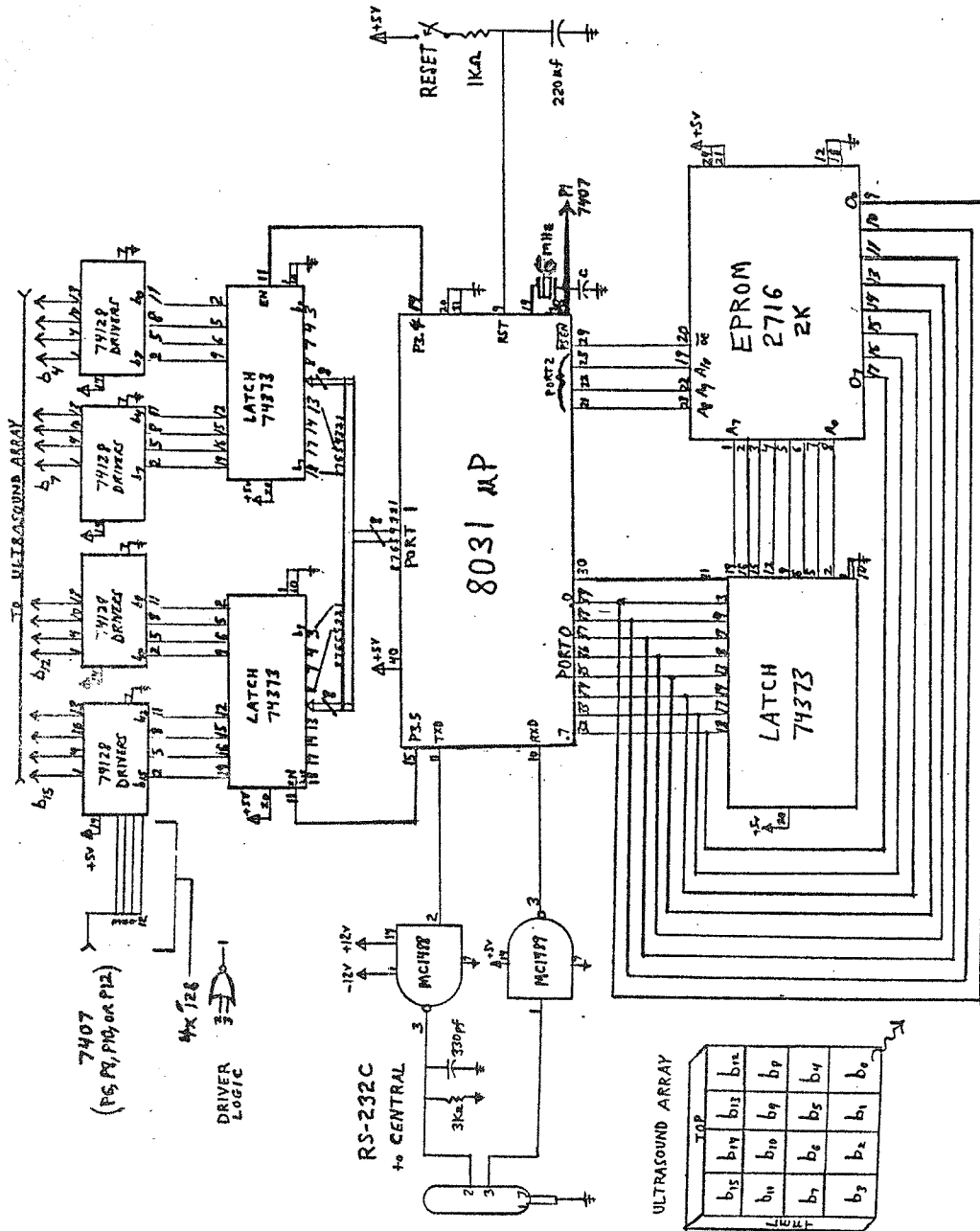


Figure 5. Fixed array controller circuit.

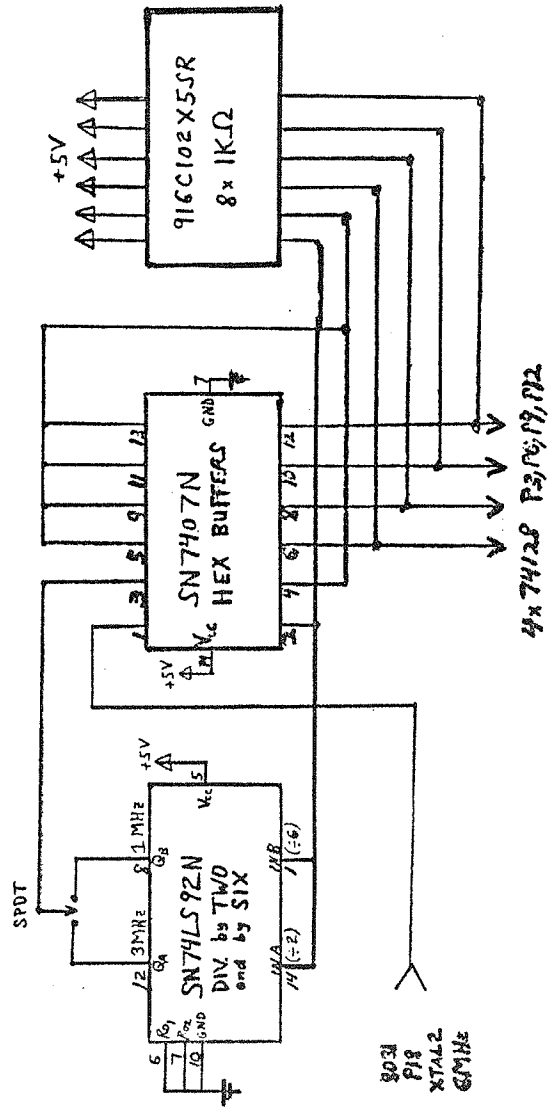


Figure 6. RF signal generation circuit for fixed array controller.

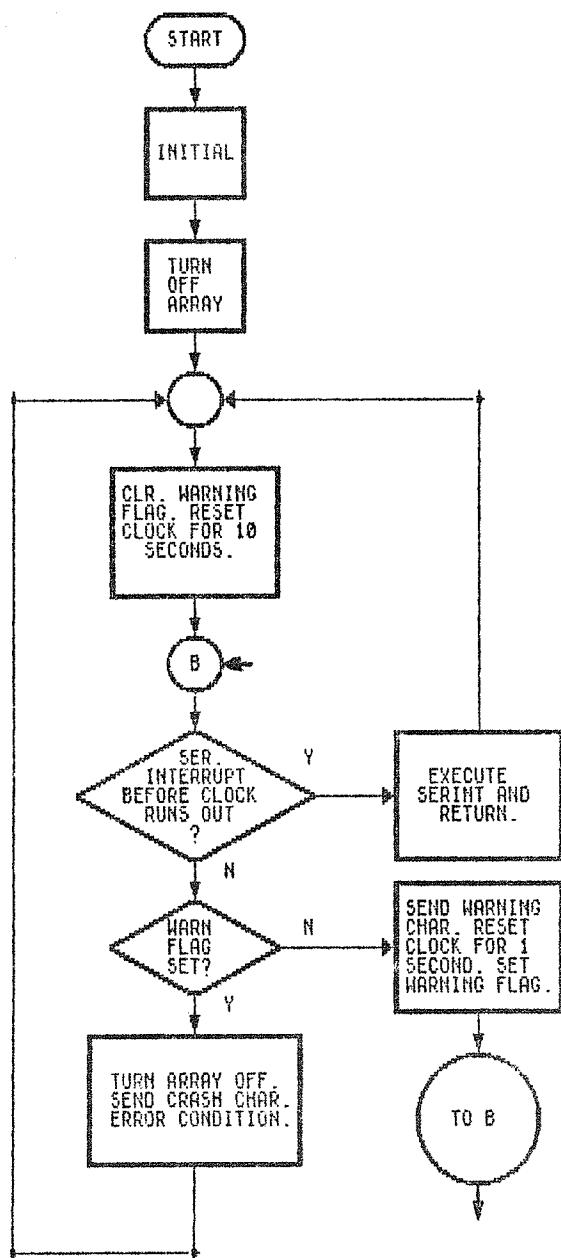


Figure 7. MAIN program flow chart.

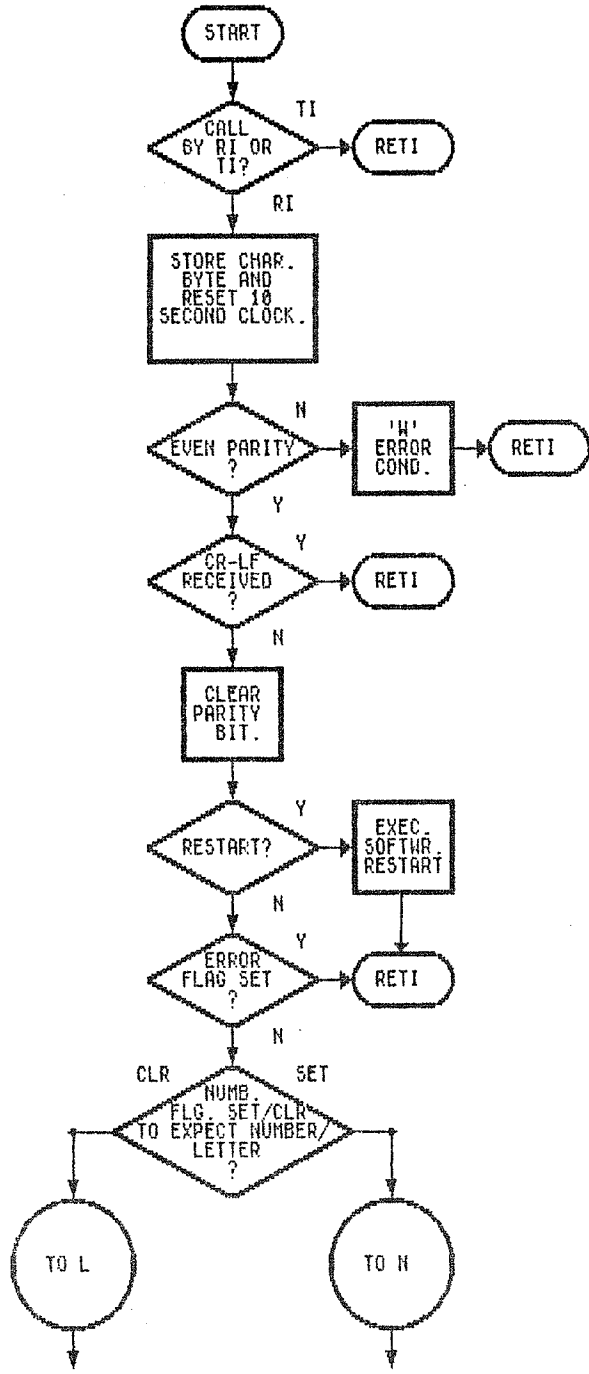


Figure 8. SERINT program flow chart.

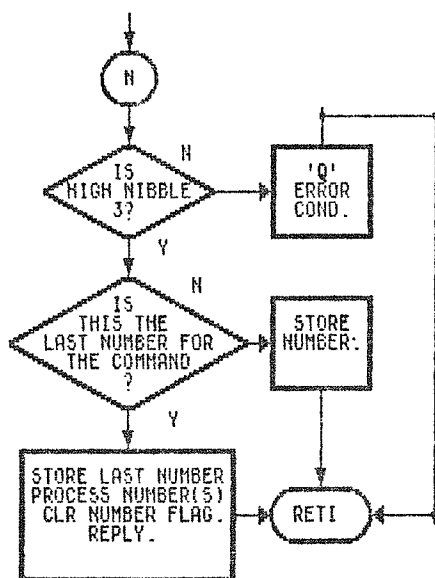
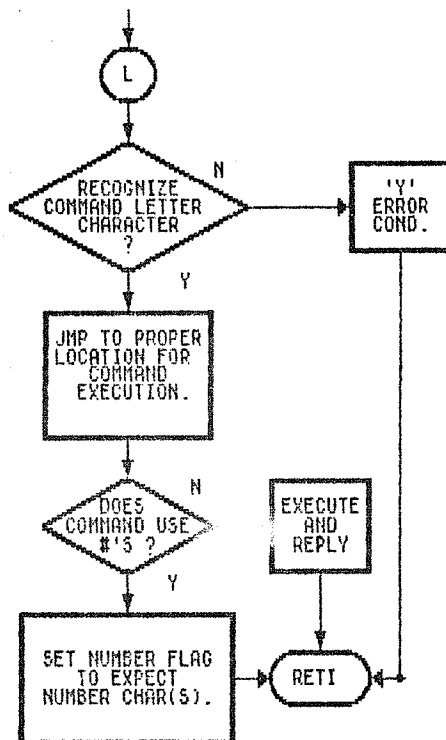


Figure 8 (continued). SERINT program flow chart.

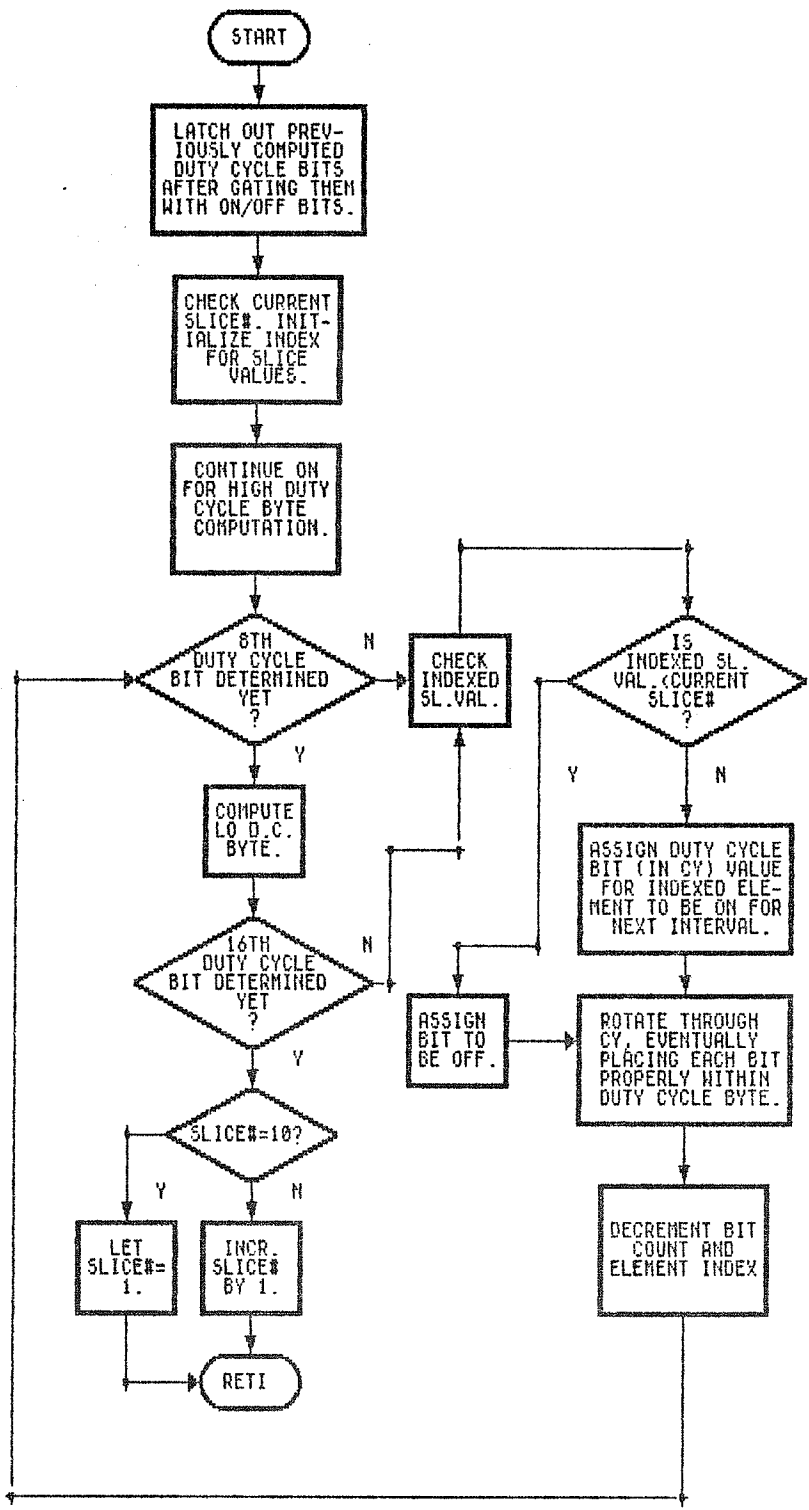


Figure 9. TIMINT program flow chart.

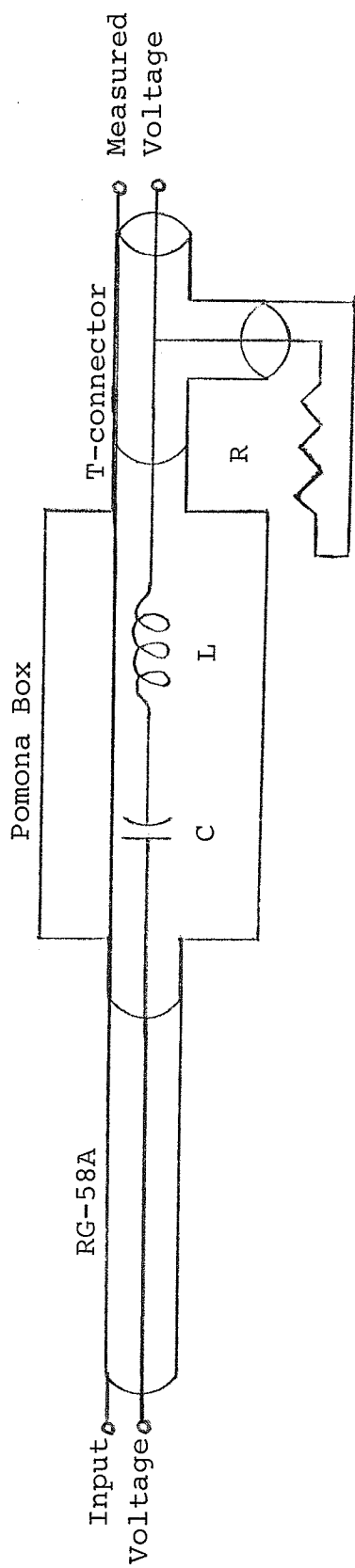


Figure 10. Bandpass filter for AC power measurement.

APPENDIX A
INTEL 8051 PROGRAM LISTING

DUTY PROGRAM LISTING

"DUTY" IS AN INTEL 8051 ASSEMBLY
LEVEL PROGRAM FOR ULTRASOUND FIXED
ARRAY CONTROL.

DUTY IS ASSEMBLED WITH AVOCET 1.09
XASM51 CROSS-ASSEMBLER ON APPLE IIE
UNDER CP/M OPERATING SYSTEM.

DUTY WAS BURNED ON APPLE WITH
HOLLISTER HMS3264 EPROM BURNER.

```

0000      F1 EQU 20H.0
0001      F2 EQU 20H.1
0002      F3 EQU 20H.2
0003      F4 EQU 20H.3
0004      F5 EQU 20H.4
0005      F6 EQU 20H.5
0006      F7 EQU 20H.6
0007      F8 EQU 20H.7
0040      DCOUNT EQU 40H
0070      TCOUNT0 EQU 70H
0071      TCOUNT1 EQU 71H
0052      R EQU 52H
004E      N EQU 4EH
0053      S EQU 53H
0044      D EQU 44H
0049      I EQU 49H
004A      J EQU 4AH
004B      K EQU 4BH
004C      L EQU 4CH
004D      M EQU 4DH
00C3      C EQU 0C3H
00D1      Q EQU 0D1H
00D7      W EQU 0D7H
00D8      X EQU 0D8H
0059      Y EQU 59H
0055      U EQU 55H
00CF      D EQU 0CFH
0048      H EQU 48H
0008      FW EQU 21H.0
007A      D0 EQU 7AH
007B      D1 EQU 7BH
007C      D2 EQU 7CH
007D      D2VAR EQU 7DH
0028      RED0B EQU 28H
0004      RED0S EQU 04H
00FF      RED1 EQU 0FFH
00FF      RED2B EQU 0FFH
0033      RED2S EQU 33H
0022      HCOUNT EQU 22H
;
0100      ORG 0100H
;
; EXPECT: ADDR CODE INSTR
;         0000 2100 AJMP MAIN
;         000B 217B AJMP TIMINT
;         0023 21BE AJMP SERINT
; (PROGRAMMED W/ EPROM BURN)
;
; "DUTY" IS A PROG. FOR INTENSITY
; CONTROL VIA DUTY CYCLE VARIATION.
;
; "MAIN" CONSISTS OF INITIALIZATION
; AND INTERRUPT ANTICIPATION AS IT
; RUNS THROUGH THE DELAY ROUTINE.

```

```

;
; "OFF" IS A ROUTINE WHICH TURNS
; ALL DRIVES OFF AND DISABLES TINT
;
; "TRANS" IS A ROUTINE WHICH WAITS FOR
; COMPLETION OF A SER. TRANSMISSION.
; (CALLED BEFORE NEXT TRANSMISSION.)
;
0100 12015B MAIN: CALL OFF
0103 758922 MOV TMOD,#22H ;BOTH MODE 2
0106 758C00 MOV TH0,#00H ;LONGEST SLICE
0109 758DCC MOV TH1,#0CCH ;300 BAUD
010C 759850 MOV SCON,#50H ;MODE 1
010F 75B802 MOV IP,#02H ;TINT HIGH PRIOR.
0112 75B850 MOV TCON,#50H ;BOTH TIMERS ON
;
; "RSMIN" IS THE RETURN DESTINATION
; FROM A SOFTWARE RESTART COMMAND
;
0115 758107 RSMIN:MOV SP,#07H ;NEW STACK
0118 752000 MOV 20H,#00H ;CLEAR ALL FLAGS
011B 7A01 MOV R2,#01H ; INIT. SLICE#
;
; "DELAY" IS USED TO PERFORM TIMING
; LOOPS AND DIRECT PROG. FLOW FOR
; THE AUTOMATIC SHUT-DOWN FEATURE
; OF THE CONTROLLER.
;
011D C208 DELAY: CLR FW
011F 757A28 DELO: MOV D0,#RED0B
0122 D57A05 LOOP0: DJNZ D0,DEL1
0125 200825 JB FW,CRASH ;WARN OR CRASH.
0128 B010 SJMP WARN ;SEND WARNING IF
012A 757BFF DEL1: MOV D1,#RED1 ;NO CHAR. REC'D.
012D D57B02 LOOP1: DJNZ D1,DEL2 ;WITHIN 10 SEC.
0130 B0F0 SJMP LOOP0 ;SHUT DOWN IF
0132 857D7C DEL2: MOV D2,D2VAR ;NONE REC'D.AFTER
0135 D57CFD LOOP2: DJNZ D2,LOOP2;ONE MORE SEC.
0138 B0F3 SJMP LOOP1
;
013A D208 WARN: SETB FW
013C 120170 CALL TRANS
013F 759955 MOV SBUF,#U
0142 757A04 MOV D0,#RED0S
0145 2008E2 JB FW,DEL1
0148 757A28 MOV D0,#RED0B
014B B0D5 SJMP LOOP0
;
014D D201 CRASH: SETB F2
014F C208 CLR FW
0151 12015B CALL OFF
0154 7599CF MOV SBUF,#D
0157 B0C6 SJMP DELO
0159 B0FE HERE: SJMP HERE ;(IGNORE)

```

```

;
; "OFF" IS A SUBROUTINE.
;
015B 75A890 OFF: MOV IE,#90H ;DISABLE TINT
015E 757DFF      MOV D2VAR,#RED2B
0161 7590FF      MOV P1,#0FFH ; '1' TURNS OFF
0164 D2B5        SETB P3.5 ; HI BYTE
0166 C2B5        CLR P3.5
0168 7590FF      MOV P1,#0FFH
016B D2B4        SETB P3.4 ; LD BYTE
016D C2B4        CLR P3.4
016F 22         RET

;
; "TRANS" IS A SUBROUTINE.
;
0170 300205 TRANS: JNB F3,SOK ;F3 SET DURING
0173 3099FA      JNB TI,TRANS ;SER. TRANS.
0176 C299        CLR TI
0178 D202        SOK: SETB F3
017A 22         RET

;
; "TIMINT" IS A TIMER INTERRUPT
;ROUTINE WHICH SETS THE BITS OF THE
;REGISTERS TO BE LATCHED OUT AT
;REGULAR INTERVALS FOR DUTY CYCLE
;CONTROL
;
017B C090 TIMINT:PUSH P1
017D C0D0      PUSH PSW
017F C0E0      PUSH ACC
0181 EF        MOV A,R7 ;"DR" HI ON/OFF
0182 4D        ORL A,R5 ;BYTE W/ HI DUTY
0183 F590      MOV P1,A ;CYCLE BYTE AND
0185 D2B5      SETB P3.5 ;LATCH OUT. REPEAT
0187 C2B5      CLR P3.5 ;FOR LO BYTES.
0189 EE        MOV A,R6 ;(NEED BOTH=0
018A 4C        ORL A,R4 ;FOR 0 OUT TO
018B F590      MOV P1,A ;TURN ON ELEMENT.)
018D D2B4      SETB P3.4
018F C2B4      CLR P3.4
0191 757108    MOV TCOUNT1,#08H ;INIT. LOOP
0194 75700B    MOV TCOUNT0,#08H ;COUNTERS
0197 785F      MOV R0,#5FH

;
;LOCATIONS 50H-5FH CONTAIN THE
;SLICE VALUES FOR EACH ELEMENT. IF AN
;ELEMENT'S SLICEVAL IS LESS THAN THE
;CURRENT SLICE#, ITS D.C. BIT IS SET
;TO KEEP THE ELEMENT OFF FOR A SLICE
;
0199 EA        LOOPHI:MOV A,R2 ;HI BYTE LOOP
019A 14        DEC A
019B C3        CLR C
019C 96        SUBB A,@R0

```

```

019D B3          CPL C
019E ED          MOV A,R5
019F 33          RLC A
01A0 FD          MOV R5,A
01A1 1B          DEC R0
01A2 D571F4     DJNZ TCOUNT1,LOOPHI
;
01A5 EA          LOOPLO:MOV A,R2 ;LO BYTE LOOP
01A6 14          DEC A
01A7 C3          CLR C
01A8 96          SUBB A,@R0
01A9 B3          CPL C
01AA EC          MOV A,R4
01AB 33          RLC A
01AC FC          MOV R4,A
01AD 1B          DEC R0
01AE D570F4     DJNZ TCOUNT0,LOOPLO
01B1 0A          INC R2 ; INCREMENT SLICE# OR
01B2 BA0B02     CJNE R2,#0BH,TFIN ;RESET TO 1
01B5 7A01          MOV R2,#01H ;IF NOW 10.
;
01B7 D0E0     TFIN: POP ACC
01B9 D0D0     POP PSW
01BB D090     POP P1
01BD 32          RETI
;
; "SERINT" IS THE SERIAL INTERRUPT
; ROUTINE WHICH ACCEPTS AND EXECUTES
; COMMANDS FROM CENTRAL. THE COMMANDS
; CONSIST OF A LETTER WHICH MAY OR
; MAY NOT BE FOLLOWED BY NUMBER(S).
; THOSE W/ NUMBER(S) HAVE FLAGS
; ASSOCIATED W/ THEM TO DIRECT
; PROGRAM FLOW FOR NUMBER PROCESSING.
;
01BE 209B05     SERINT:JB RI,PAR ;RETURN IF
01C1 C299          CLR TI ;SELF-CALLED
01C3 C202          CLR F3
01C5 32          RETI
01C6 C208     PAR: CLR FW
01C8 757A2B     MOV D0,#RED0B
01CB 757BFF     MOV D1,#RED1
01CE 857D7C     MOV D2,D2VAR
01D1 E599          MOV A,SBUF ;RECEIVE CHAR.
01D3 30D00C     JNB P,MP ;IF ODD PAR., THEN
01D6 D201          SETB F2 ;ERROR.SEND "W".
01D8 315B          CALL OFF ;ELSE PROCEED.
01DA 3170          CALL TRANS
01DC 7599D7     MOV SBUF,#W
01DF C29B          CLR RI
01E1 32          RETI
01E2 C2E7     MP: CLR ACC.7 ;MASK PAR. BIT
01E4 F5F0          MOV B,A ;SAVE CHAR IN B.
;

```

```

01E6 B40D03 CR: CJNE A,#0DH,LF ;IGNORE LINE
01E9 C298 CLR RI ;FEED CHAR.
01EB 32 RETI
01EC B40A03 LF: CJNE A,#0AH,CHRST ;IGNORE
01EF C298 CLR RI ;CARRIAGE RET. CHAR.
01F1 32 RETI
;
01F2 C3 CHRST: CLR C
01F3 9452 SUBB A,#R ;SOFTWARE RESTART
01F5 6062 JZ RST
01F7 300103 JNB F2,TYPE ;ONLY ACCEPT "R"
01FA C298 CLR RI ;IF F2 SET
01FC 32 RETI
;
01FD 200071 TYPE: JB F1,NUMBH ;F1 SET/CLR MEANS
0200 ;EXPECT NUMBER/LETTER
;
0200 E5F0 COMM: MOV A,B ;CHECK CHAR. AND
0202 C3 CLR C ;BRANCH ACCORDINGLY
0203 944E SUBB A,#N
0205 607B JZ NOPP ;NO OPERATION
0207 E5F0 MOV A,B
0209 C3 CLR C
020A 9453 SUBB A,#S
020C 606F JZ STOPP ;STOP,DRIVES OFF,
020E E5F0 MOV A,B ;DISABLE TINT
0210 C3 CLR C
0211 9442 SUBB A,#42H ; "B"
0213 607E JZ BSET ; BEGIN HEATING
0215 E5F0 MOV A,B ; FROM REGISTERS
0217 C3 CLR C
0218 9444 SUBB A,#D ;EXPECT 4 NUMBERS
021A 6057 JZ DPREP ;FOR ON/OFF INFO
021C E5F0 MOV A,B
021E C3 CLR C
021F 9441 SUBB A,#41H ; "A"
0221 6068 JZ A1$ ;EXPECT A NUMBER FOR
0223 E5F0 MOV A,B ;ALL 16 SLICE VALUES
0225 C3 CLR C
0226 9449 SUBB A,#I ;EXP. THE NUMBER OF
022B 6063 JZ I1$ ;THE ELEMENT WHOSE
022A E5F0 MOV A,B ;SLICEVAL IS DESIRED
022C C3 CLR C ; ...TO BE KNOWN.
022D 944D SUBB A,#M
022F 6060 JZ M1$; ...TO BE INCREMENTED.
0231 E5F0 MOV A,B
0233 C3 CLR C
0234 944C SUBB A,#L
0236 6057 JZ L1$; ...TO BE DECREMENTED.
023B E5F0 MOV A,B
023A C3 CLR C
023B 944B SUBB A,#K ;INCREMENT ALL 16
023D 604A JZ INCRA1 ;SLICEVALS BY 1.
023F E5F0 MOV A,B

```

```

0241 C3          CLR C
0242 944A        SUBB A,#J ;DECREMENT ALL 16
0244 6041        JZ DECRA1 ;SLICEVALS BY 1.
0246 E5F0        MOV A,B
0248 C3          CLR C
0249 944B        SUBB A,#H
024B 6069        JZ DISPL1 ;DISPLAY ALL VALUES.

;
024D D201        INVC: SETB F2 ;IF NO COMM. CHAR.
024F 315B        CALL OFF ;IS RECOGNIZED,
0251 3170        CALL TRANS ;ERROR. SEND "Y".
0253 759959      MOV SBUF,#Y ;ACCEPT "R" ONLY.
0256 C298        CLR RI
0258 32          RETI

;
0259 315B        RST: CALL OFF ;ALL OFF
025B 7400        MOV A,#00H ;CLR A AND B
025D F5F0        MOV B,A
025F C298        CLR RI
0261 3170        CALL TRANS
0263 7599C3      MOV SBUF,#C ;REPLY
0266 754115      MOV 41H,#15H
0269 754201      MOV 42H,#01H ;PUSH RETURN
026C C041        PUSH 41H ;ADDRESS(RSMIN:)
026E C042        PUSH 42H ;ONTO STACK
0270 32          RETI

;
0271 806D        NUMB: SJMP NUMB ;INTERMEDIATE JUMP.
; SEVERAL SUCH JUMPS ARE REQUIRED
; FOR SUCCESSFUL PROG. ASSEMBLY.
;
0273 D200        DPREP: SETB F1 ;EXPECT NUMBER CHAR.
0275 D203        SETB F4 ;FOR PROG. FLOW
0277 754004      MOV DCOUNT,#04H ;INIT. LOOP
027A C298        CLR RI ;COUNTER
027C 32          RETI

;
027D 315B        STOPP: CALL OFF ;ALL OFF
027F 3170        NOPP: CALL TRANS
0281 7599C3      MOV SBUF,#C ;REPLY
0284 C298        CLR RI
0286 32          RETI

;
0287 8043        DECRA1: SJMP DECRA1
;
0289 802D        INCRA1: SJMP INCRA1
;
028B 8016        A1$: SJMP A$ ;INTERMEDIATE JUMPS
028D 801B        I1$: SJMP I$ ;TO MEANINGFUL
028F 801E        L1$: SJMP L$ ;LOCATIONS IN
0291 8018        M1$: SJMP M$ ;PROGRAM MEMORY.
;
0293 3170        BSET: CALL TRANS
0295 7599C3      MOV SBUF,#C

```



```

0298 7A01      MOV R2,#01H ;INITIALIZE SLICE#
029A 757D33    MOV D2VAR,#RED2S
029D 75A892    MOV IE,#92H ;ENABLE TINT,START
02A0 C298      CLR RI      ;DUTY CYCLE.
02A2 32        RETI

;
02A3 D204      A$:  SETB F5  ;FLAGS ARE SET FOR
02A5 800A      SJMP FIN$ ;PROG. FLOW
02A7 D205      I$:  SETB F6
02A9 8006      SJMP FIN$
02AB D206      M$:  SETB F7
02AD 8002      SJMP FIN$
02AF D207      L$:  SETB F8
02B1 D200      FIN$: SETB F1  ;EXPECT NUMBER CHAR.
02B3 C298      CLR RI
02B5 32        RETI

;
02B6 807D      DISPL1: SJMP DISPL2

;
02BB 7950      INCRAL: MOV R1,#50H      ;INCR. ALL
02BA B70A02    KLOOP:  CJNE @R1,#0AH,INCA ;LESS THAN
02BD 8001      SJMP INCONT      ;10
02BF 07        INCA:  INC @R1
02C0 09        INCONT: INC R1
02C1 B960F6    CJNE R1,#60H,KLOOP
02C4 3170      CALL TRANS
02C6 7599C3    MOV SBUF,#C ;REPLY
02C9 C298      CLR RI
02CB 32        RETI

;
02CC 7950      DECRAL: MOV R1,#50H      ;DECR. ALL
02CE B70002    JLOOP:  CJNE @R1,#00H,DECA ;GREATER
02D1 8001      SJMP DECONT      ;THAN 0
02D3 17        DECA:  DEC @R1
02D4 09        DECONT: INC R1
02D5 B960F6    CJNE R1,#60H,JLOOP
02D8 3170      CALL TRANS
02DA 7599C3    MOV SBUF,#C ;REPLY
02DD C298      CLR RI
02DF 32        RETI

;
;NUMBER CHARACTER REFERS TO THE ASCII
;CHAR. W/ 3 IN THE HIGH NIBBLE AND
;A VALUE BET. 0 AND 15 IN THE LOW.
;
; 0,1,2,3,4,5,6,7,8,9,=,;,<,>=?
;
;THEY WILL BE SENT AND RECEIVED
;W/ EVEN PARITY.
;
02E0 E5F0      NUMB:  MOV A,B      ;LOAD NUMBER
02E2 20E608    JB ACC.6,INVD ;CHARACTER.
02E5 30E505    JNB ACC.5,INVD ;ERROR IF HI
02E8 30E402    JNB ACC.4,INVD ;NIBBLE NOT

```

```

02EB 800C          SJMP VD          ;EQUAL TO 3.
;
02ED D201          INVD: SETB F2          ;SEND "Q" AND
02EF 315B          CALL OFF          ;ACCEPT "R" ONLY
02F1 3170          CALL TRANS
02F3 7599D1        MOV SBUF,#Q
02F6 C298          CLR RI
02F8 32           RETI
;
02F9 540F          VD:  ANL A,#0FH ;MASK HI NIBBLE.
02FB 200311        JB F4,DATA ;ACC. CONTAINS
02FE 200436        JB F5,ALL ;ACTUAL VALUE.
0301 200571        JB F6,ONE
0304 20066E        JB F7,ONE ;JUMP ACCORDING
0307 20076B        JB F8,ONE ;TO WHICH FLAG SET
030A C200          CLR F1
030C C298          CLR RI
030E 32           RETI
;
030F F5F0          DATA: MOV B,A          ;STORE 1ST OF 4
0311 E540          MOV A,DCOUNT ;VALUES IN LOC.
0313 2430          ADD A,#30H ;34H...4TH IN 31H
0315 F9           MOV R1,A
0316 A7F0          MOV @R1,B
0318 D54017        DJNZ DCOUNT,MORDAT
;
031B E534          DFIN: MOV A,34H ;WHEN DCOUNT=0,MERGE
031D C4           SWAP A ;THE NON-ZERO NIBBLE
031E 2533          ADD A,33H ;OF EACH INTO 1 BYTE
0320 F4           CPL A ;AT R7(COMPLEMENTED
0321 FF           MOV R7,A ;FOR DRIVER LOGIC).
0322 E532          MOV A,32H ;HI ON/OFF BYTE.
0324 C4           SWAP A
0325 2531          ADD A,31H ;DO SAME FOR LO
0327 F4           CPL A ;ON/OFF BYTE AT R6.
0328 FE           MOV R6,A
0329 3170          CALL TRANS
032B 7599C3        MOV SBUF,#C ;REPLY
032E C203          CLR F4
0330 C200          CLR F1 ;EXPECT LETTERS AGAIN
0332 C298          MORDAT:CLR RI
0334 32           RETI
;
0335 806F          DISPL2: SJMP DISPLA
;
0337 F5F0          ALL:  MOV B,A          ;IF SLICEVAL > 10,
0339 740A          MOV A,#0AH ;TOO HIGH. IGNORE
033B C3           CLR C ;BUT REPLY.
033C 95F0          SUBB A,B
033E 402E          JC TOOHI
0340 E5F0          MOV A,B
;
0342 F550          NOTOHI:MOV 50H,A ;IF NOT TOO HIGH,
0344 F551          MOV 51H,A ;THEN ASSIGN THE

```

```

0346 F552      MOV 52H,A ;SLICEVAL TO EVERY
0348 F553      MOV 53H,A ;ELEMENT'S LOC.
034A F554      MOV 54H,A
034C F555      MOV 55H,A
034E F556      MOV 56H,A
0350 F557      MOV 57H,A
0352 F558      MOV 58H,A
0354 F559      MOV 59H,A
0356 F55A      MOV 5AH,A
0358 F55B      MOV 5BH,A
035A F55C      MOV 5CH,A
035C F55D      MOV 5DH,A
035E F55E      MOV 5EH,A
0360 F55F      MOV 5FH,A
0362           ;
0362 3170      CALL TRANS ;REPLY "C" IF NOT
0364 7599C3    MOV SBUF,#C ;TOO HIGH
0367 C204      ALLFIN:CLR F5
0369 C200      CLR F1 ;EXP. LETTER
036B C298      CLR RI
036D 32        RETI
;
036E 3170      TOOHI: CALL TRANS ;SEND "X" IF
0370 7599D8    MOV SBUF,#X ;TOO HIGH
0373 80F2      SJMP ALLFIN
;
0375 2450      ONE:  ADD A,#50H ;SLICEVAL FOR
0377 F9        MOV R1,A ;ELEMENT N IS AT
037B 200514    JB F6,IFIN ;LOC. (50H + N)
037B 200603    JB F7,INCR
037E 200708    JB F8,DECR
;
0381 B70A02    INCR: CJNE @R1,#0AH,INCONE ;INCR. IF
0384 8009      SJMP IFIN ;<10 WHEN
0386 07        INCONE:INC @R1 ;F7 SET
0387 8006      SJMP IFIN
0389 B70002    DECR: CJNE @R1,#00H,DECONE ;DECR. IF
038C 8001      SJMP IFIN ;>0 WHEN
038E 17        DECONE:DEC @R1 ;F8 SET
038F E7        IFIN:  MOV A,@R1
0390 2430      ADD A,#30H ;ONLY REPLY WHEN
0392 30D002    JNB P,NUMOUT ;F6 SET
0395 D2E7      SETB ACC.7
0397 3170      NUMOUT:CALL TRANS ;REPLY W/ NUMBER
0399 F599      MOV SBUF,A ;CHAR. FOR LATEST
039B C205      CLR F6 ;SLICEVAL OF
039D C206      CLR F7 ;DESIRED ELEMENT.
039F C207      CLR F8 ;SEND W/ EVEN PAR
03A1 C200      CLR F1 ;EXPECT LETTER CHAR.
03A3 C298      CLR RI
03A5 32        RETI
;
03A6 3170      DISPLA:CALL TRANS ;SEND LF-CR
03A8 75990A    MOV SBUF,#0AH ;TO ADJUST

```

```

03AB 3170          CALL TRANS    ;DISPLAY
03AD 75998D       MOV SBUF,#8DH
03B0 75225F       MOV HCOUNT,#5FH ;INITIALIZE.
03B3 EF          MOV A,R7      ;LOAD HI ON/OFF
03B4 33          DISTAT:RLC A      ;BYTE.TEST EACH
03B5 4014         JC OFFVAL    ;BIT.SEND '*' IF
03B7 A922         MOV R1,HCOUNT ;OFF,ELSE SEND
03B9 F5F0         MOV B,A      ;INTENSITY VAL.
03BB E7          MOV A,@R1
03BC 2430         ADD A,#30H
03BE 30D002       JNB P,SENDIS ;EVEN PAR.
03C1 2480         ADD A,#80H
03C3 3170         SENDIS:CALL TRANS
03C5 F599         MOV SBUF,A
03C7 E5F0         MOV A,B      ;RELOAD TO ROTATE.
03C9 8005         SJMP HCHECK
03CB 3170         OFFVAL:CALL TRANS
03CD 7599AA       MOV SBUF,#0AAH ;SEND '*'.
03D0 1522         HCHECK:DEC HCOUNT
03D2 3010DF       JNB 10H,DISTAT
03D5 3011DC       JNB 11H,DISTAT
03D8 3170         CALL TRANS
03DA 75990A       MOV SBUF,#0AH ;SEND LF-CR
03DD 3170         CALL TRANS ;AFTER EACH
03DF 75998D       MOV SBUF,#8DH ;FOUR CHARS.
03E2 3012CF       JNB 12H,DISTAT
03E5 EE          MOV A,R6      ;LOAD LO ON/
03E6 3013CB       JNB 13H,DISTAT ;OFF BYTE FOR
03E9 C298         CLR RI      ;ROTATION.
03EB 32          RETI ;RETURN AFTER ALL 16.

;
0000             END

```

APPENDIX B

PSIO CARD CONFIGURATION FOR APPLE IIe

P.S.I.O. TEXT CONFIGURATION:

SLOT NUMBER	PHAN 2	REAL 1
COLD START STRING		
SEND STRING TO	PARALLEL	
FORM WIDTH	0	96
FORM LENGTH	0	54
AUTO LINEFEED	DISABLED	ENABLED
VIDEO MODE	ENABLED	DISABLED
DELAY AFTER CR	NONE	
LINEFEED MASK	ENABLED	
CONVERT LOWER CASE	DISABLED	
SHIFT MOD	DISABLED	
XON/XOFF	ENABLED	
DUPLEX MODE	FULL	
BAUD RATE	300	
PARITY	EVEN	
DATA FORMAT	7 DATA 1 STOP	

APPENDIX C

BASIC PROGRAM LISTING

IREM "TRY1" IS AN APPLESOFT BASIC PROGRAM FOR INTEL 8031 ARRAY CONTROLLER INTERFACING.

!LOAD TRY1

!LIST

```
10 D$ = CHR$(13) + CHR$(4)
20 PRINT D$;"IN#0"
30 INPUT COUT$
40 PRINT D$;"PR#2"
50 PRINT COUT$;
60 PRINT D$;"IN#2"
70 GET CIN$
80 PRINT D$;"PR#0"
90 PRINT CIN$;
100 GOTO 20
110 END
```

APPENDIX D
FILTER PARAMETER VALUES

RLC BANDPASS FILTER PARAMETERS

$$f = 1 \text{ MHz}$$

$$R = 50 \Omega \quad L = 64.27 \mu\text{H}$$

$$Q = 2\pi f L / R = 8.12$$

$$C = 390 \text{ pF} \quad f = \sqrt{1/LC} = 1.005 \text{ MHz}$$

$$f = 3 \text{ MHz}$$

$$R = 50 \Omega \quad L = 19.04 \mu\text{H}$$

$$Q = 7.13$$

$$C = 150 \text{ pF} \quad f = 2.978 \text{ MHz}$$

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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

THE GRADUATE COLLEGE

DECEMBER 1984

WE HEREBY RECOMMEND THAT THE THESIS BY

DAVID CHARLES GRETHEN

ENTITLED THE DESIGN OF AN ULTRASOUND FIXED ARRAY CONTROLLER
FOR USE IN HYPERTHERMIA

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE

Richard L. Magin

Director of Thesis Research

J. W. Ernst

Head of Department

Committee on Final Examination†

Chairman

† Required for doctor's degree but not for master's.