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COMPUTER CONTROL OF A MICROGRAVITY MAMMALIAN CELL BIOREACTOR

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INTRODUCTION

Our bioreactor is an electro-mechanical cell growth system cell requiring rigorous control of slowly changing parameters, many of which are so dynamically interactive that computer control is a necessity. The process control computer will have two main functions. First, it will provide continuous environmental control utilizing low signal level transducers as inputs and high powered control devices such as solenoids and motors as outputs. Secondly, it will provide continuous environmental monitoring including mass data storage and periodic data dumps to a supervisory computer.

The supervisory computer will be evolved with data analysis, plotting, and system parameters trend prediction.

This paper outlines the initial steps taken in developing a completely menu driven and totally automated computer control system for the bioreactor.

PROCESS CONTROL REQUIREMENTS

General Approach

The initial step in developing the process control system is to supply sufficient generalized control to determine individual parameter interaction. The data thus obtained will be used to develop the more sophisticated control loops. The requirements for the process control loops are divided into three major categories: dynamic, steady state, and/or on/off control. Each of these loops are described by the four following criteria:

- Limits - defines the maximum and minimum range of operation of the control loop
- Perturbations - sources of change or interferences to a particular control loop
- Control element - sensor used in feedback loop
- Effector - device acted on to provide control

Dynamic Control Loop

The dynamic control loops regulate pH, temperature, and gases, which require multilevel, interactive, control actions for optimal operating conditions. For example, any changes in oxygen flow rate or pressure will result in an equal change in dissolved CO_2 concentration followed by a shift in pH. This complicated interweaving of individual parameters and the long delay times for recorded responses, mean classical control approaches such as PID loops may not be adequate or reliable enough to maintain the desired degree of control. Moreover, the well known problem of biochemical sensor drift must be taken into account. Initial testing of the system is necessary in order to establish the intensity of parameter interaction in relation to the amount of transducer signal drift before any reliable interactive controls can be developed.

Steady State Control Loop

The steady state control loops regulate fluid flow rates and the reaction vessel stirrer motor's rpm. These loops maintain the flow rates and rpm at a set operating point independent of on-going system changes. The operator may change these fixed rates by a menu entry on the computer/operator display device.

On/Off Control Loop

The on/off control loops regulate pressure by activating a relay or solenoid based on the status of a fixed setpoint.

DEVELOPMENTAL REQUIREMENTS

General Developmental Requirements

Developmental flexibility in meeting time schedules and accommodating alterations in the bioreactor fluid system has resulted in four additional requirements.

a. Input/output requirements

   The process control computer must be able to interface with a variety of analog inputs and provide a wide range of analog outputs. At present, these include 0-5 V dc (input and output), digital (input and output), 4-20 mA (input), and 0-20 V (output). In addition, the process controller must be able to communicate and exchange information with a separate supervisory computer.

b. Power/size requirements

The process controller must fit within a NASA Shuttle storage locker and consume no more than 80 watts. The maximum line wattage allowed on one line in the Shuttle is 125 watts. The Shuttle has three such lines. If a project requires two such lines, then that leaves one line for all the other projects and the crew. The same reasoning applies to the size limitation. As a general rule, the larger and more energy hungry a project is, the more difficult it is to get it into the Shuttle.

c. Programming requirements

The process controller must utilize a programming language which is compatible with a dynamically changing system and is easily understood by other members of the team. The programming language used during development must be usable able completion of the system or replaceable at this point without changing any electronic or fluid hardware. In the early stages, significant progress is expected in a short period of time. As an example, assembly language had initially been considered because it is one of the fastest and most compact of all the languages, but it is very difficult and time consuming to make large changes to programs in this language. An army of programmers would be needed to keep up with the fast research pace, and when all was said and done, only the programmers would be able to understand what the control program was really doing.

d. Support reliability requirements

The process controller must be supported by the manufacturer in terms of required modification and I/O boards. The point here is not to purchase a computer system whose manufacturer will out go out of business next month or who is unwilling to accept contract work for certain necessary modifications of sections needed to meet flight specifications. As an example, as the process control computer will be operated off of Shuttle dc power, a commercial process controller's ac power supply will be replaced. In some commercial process controllers, this would require a modification of the basic operating system software. Due to the complexity of some of the process controllers and the fact that the source code for the operating system is not provided to the users, only the manufacturer can make these changes.

Market Research

Guided by the above requirements, a comprehensive market research for a process controller was undertaken. The survey showed two types of process control units generally suitable for our application. The results of the survey are broken down into two major categories.

a. Commercially pre-packaged industrial process controllers

1. Advantages

The first group are the large industrial process controllers normally seen at chemical and oil refinery plants. These systems are generally very fast and can do just about anything. They have their own programming language and a set number of I/O boards (usually 6-10 different boards).

2. Disadvantages

The major disadvantage of this line of process controllers is that all analog computer interfacing must be made through one of these 6-10 different boards. For special input needs to the computer not supported by one of the 6-10 cards, the userards, the user must build special interface boards. This can easily lead to a significant increase in hardware. Another disadvantage most of these units have is that they are very large and power hungry. The few controllers which fall within initial size limitations (1 NASA Shuttle storage box) have other disadvantages. The customer must use the programming language supplied with the system. If this is insufficient to support the final version of the bioreactor, there is no way to change to another language. The customer is limited to a single vendor for both hardware supplies and support. And finally, the amount of programming space is inadequate. Most of these systems were designed for simple short control operations with a maximum of 40K bytes of programming space and no mass storage of data capability.

b. Bus level card process controller

1. General

These process controllers consist of individual computer boards which the user selects to make up the computer. Basically, the user builds his own computer from the board up. The actual central processing units can range from memory mapped or I/O mapped 8-bit microprocessors to the full 16 bits.

2. Advantages

There are several types of card level bus structures. The STD card system is one of the smallest and best supported of all the card systems. There are over 300 different manufacturers of STD cards and a variety of programming languages to choose from. In addition, the user can design and build his own interface boards and integrate them directly into the system without going through any other interface board. Mass memory storage is available in many different forms including bubble storage.

3. Disadvantages

The disadvantage of the 16-bit computer boards is their speed. Most STD cards on the market can handle up to a 4 MHz clock frequency, but the 16-bit boards operate at a much higher rate. The result is a limitation of variety of support I/O boards which can be utilized because the 16-bit CPU wants information faster than the support boards can deliver. This especially tends to be the case for "smart" support I/O boards which have their own microprocessor (i.e., smart analog input cards, etc.).

On the other hand, the 8-bit microprocessors can only address up to 64K bytes of memory cells. Since it takes 4 bytes of memory to store a real number, programming space becomes a real issue. In addition, a card level system requires the user to write the software drivers that will integrate the individual boards into a working system. This is an advantage in that the user can design his own boards and integrate them directly into the system, but is a disadvantage in that more programming space must be utilized leaving less for the actual control system.

Computer Selection Based on Survey

After an extensive market research and a consideration of all requirements, an 8-bit Z80 orientated STD card system with a multitasking basic programming language was chosen as the process control computer. This bus structure has flown with success on past Shuttle missions.

The multitasking basic programming language is understood by all and easily modified. In addition, each task is a separate entity and can be executed at different intervals. Each analog input and output board has its own task, and one task is reserved for an expert system.

Computer Operating Configuration

The bioreactor process control computer will be involved with a variety of operations. As seen in figure 4-7, the computer will not only interface with the bioreactor by means of transducers and effectors, but will also interface to printers, display panels, mass data storage devices, and other computers. The computer will utilize its sensors and effectors to control the bioreactor and periodically send formatted data to the printer, display terminal, and bubble memory card. Data will also be dumped both periodically and on-demand to the supervisory computer. When assistance is necessary, the computer will be able to telephone a control operator and transmit data and receive instructions. The computer will also provide a broad real-time view of the status of the bioreactor by means of the LED display board.

Computer Board Layout

The bioreactor process control computer, as seen in figure 8, consists of 12 cards. The CPU, Ram/Rom, serial, and modified CPU cards make up a functional computer. The rest of the cards are the computer's interface to the real analog world. Each interface card serves a unique function.

Analog Input Cards

Each of the 8-channel, 12-bit resolution, analog input cards has the ability to interface to a variety of signal inputs. This unique feature is due to the onboard computer located on each card which can be software programmed to interpret a variety of signals such as thermal couples, pressure transducers, or a variety of voltage ranges such a millivolts or volts.

Analog Output Cards

Each of the 4-channel, 12-bit resolution, analog output channels is capable of delivery up to 10 V in steps of .01 volts. These cards must be interfaced with off-board power drivers for high power devices.

Digital Input/Output Card

The digital I/O card consists of 64 channels which can operate as either TTL input or TTL output. The card will be used to detect switch closures, drive the LED display panel, and control opto-isolated relays.

Motor Control Card

The motor control card will be used to control stepper motors. If high powered steppers are required, then an external driver board will also be needed.

CONCLUSION

Although standard analog control would suffice for the simple control requirements, an industrial grade process control computer is required for the more involved processes normally requiring a great deal of analog circuitry and real-time human intervention of highly skilled personnel. Figure 4-1 outlines the control setup and requirements of the bioreactor as it now stands.

The 8-bit STD bus structure is adequate for an application consisting of slow changing parameters. However, if several PID type control loops are required in the end product, then these functions will need to be implemented a custom designed single board, STD control board which communicates with the main process controller. In this arrangement, the process controller passes parameters to the control boards, but is not involved with the continuous detail level control.

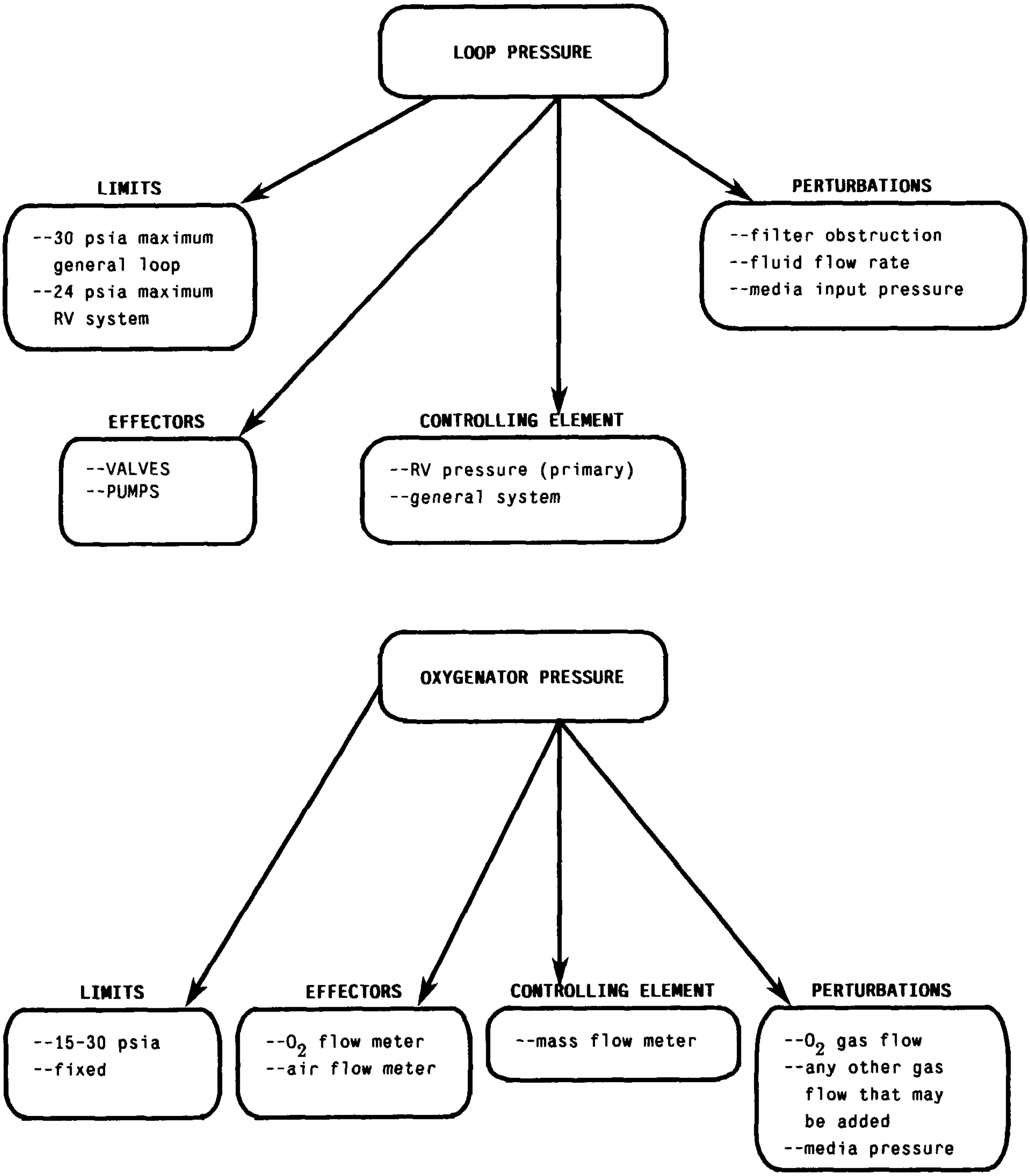


Figure 4-1.- System control requirements.

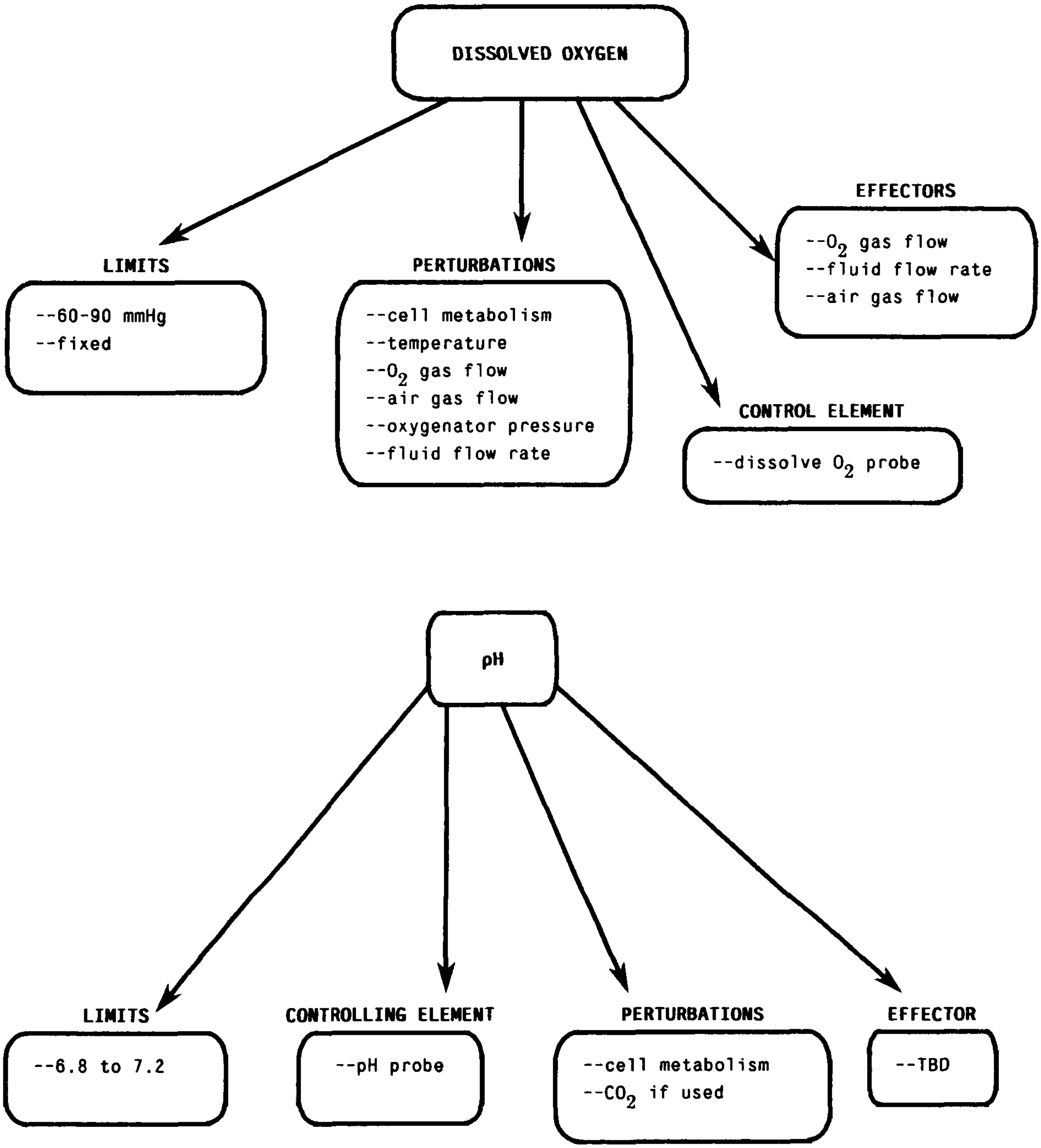
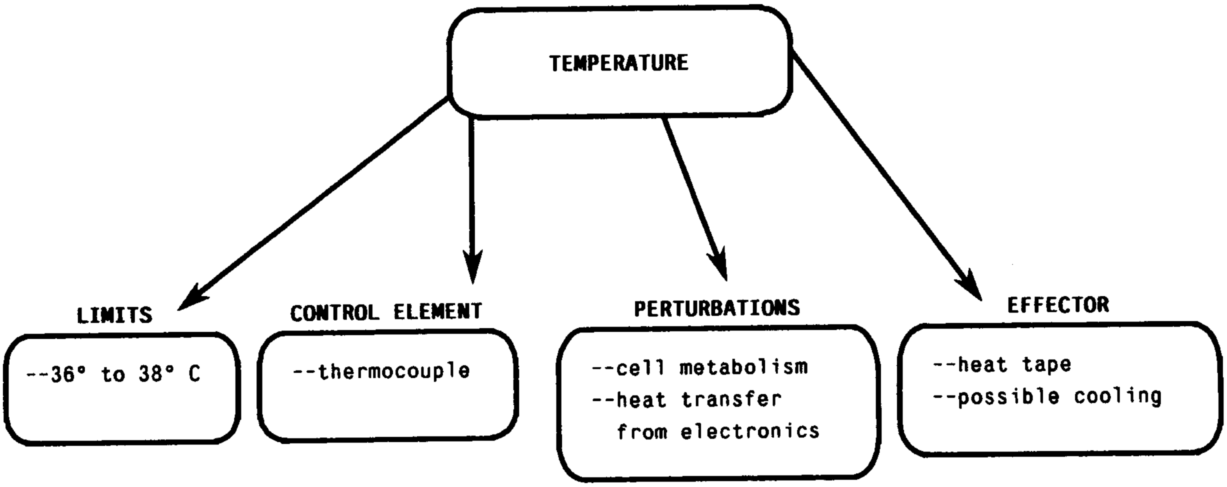


Figure 4-2.- System control requirements (continued).



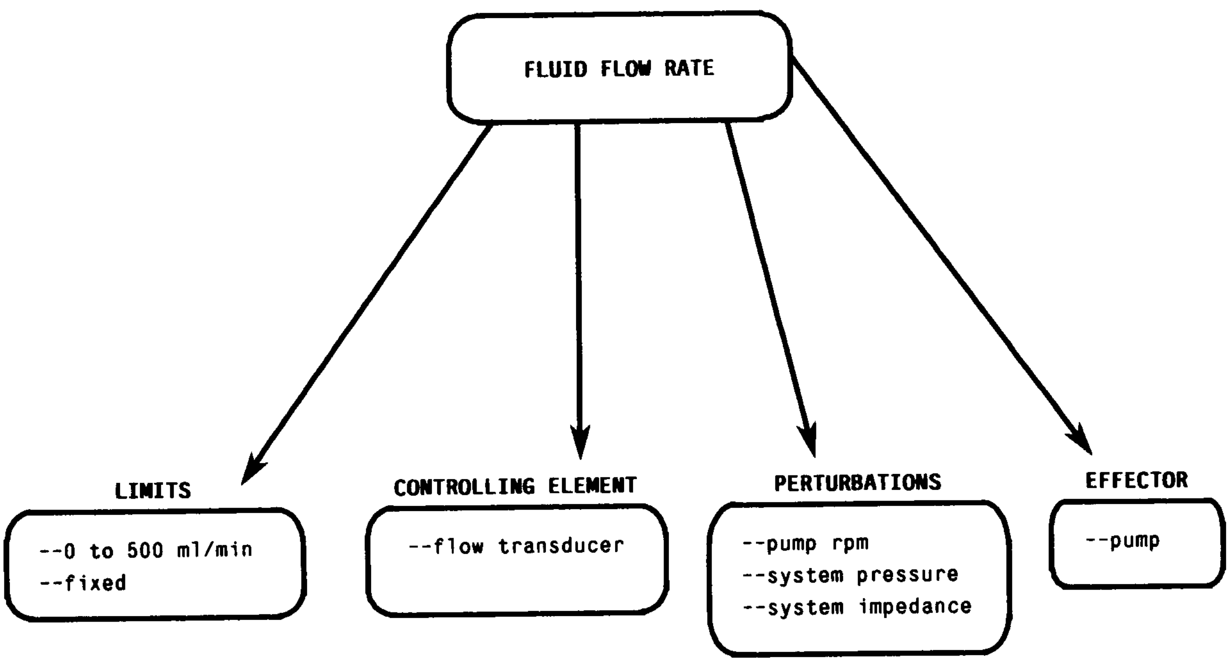


Figure 4-3.- System control requirements (concluded).

HARDWARE REQUIREMENTS

ANALOG I/O
DIGITAL I/O
FREQUENCY INPUTS
4-20 mA INPUTS
RS232
INTERFACABLE TO HIGH POWER DEVICES
--MOTORS
--HEAT TAPES

FLEXIBILITY REQUIREMENTS

--NUMBER OF BOARDS
--MULTIVENDOR

SOFTWARE REQUIREMENTS

--LANGUAGE EASILY UNDERSTOOD BY ALL
--LANGUAGE THAT EASILY HANDLES FREQUENT CHANGES
--NEED ABILITY TO CHANGE LANGUAGES IF NECESSARY

Figure 4-4.- Functional requirements.

LARGE INDUSTRIAL SYSTEMS | **STD BUS**

ADVANTAGES

LARGE INDUSTRIAL SYSTEMS:

--built-in language
--drivers provided
--monitor power

STD BUS:

--choose a language
--abundance of vendors
--complete control of bus
--bus flow several times
--being strongly considered as generic computer for NASA?

DISADVANTAGES

LARGE INDUSTRIAL SYSTEMS:

--must use their language
--cannot modify or add new drivers
--single vendor---few boards
--power hungry

STD BUS:

--write own drivers
--choose a language

Figure 4-5.- Market research.

	µMAC5000	Fluke	Burr Brown	Std Buss
I.				
Inputs				
1. Transducers	yes	yes	yes	yes
2. Keyboard	no	no	no	yes
Outputs				
1. Transducers	yes	yes	yes	yes
2. Motors	yes	yes	yes	yes
3. Solenoids	relay	relay	relay	direct
4. Display	no	no	no	yes
5. Heat Tape	yes	yes	yes	yes
Cooling and Power				
1. 100 watt limit	yes	no	yes	yes
2. Cooling fans	yes	yes	yes	yes
Size				
1. Computer-locker	$\frac{3}{4}$	1	$\frac{1}{2}$	$\frac{1}{4}$
2. Entire system	2	>2	$1\frac{3}{4}$	$1\frac{1}{4}$
II. SOFTWARE				
1. 32k of Eprom?	yes	no	yes	yes
2. Data logging?	no	no	no	yes
3. Communication?	yes	yes	yes	yes

Figure 4-6.- Bioreactor computer comparisons.

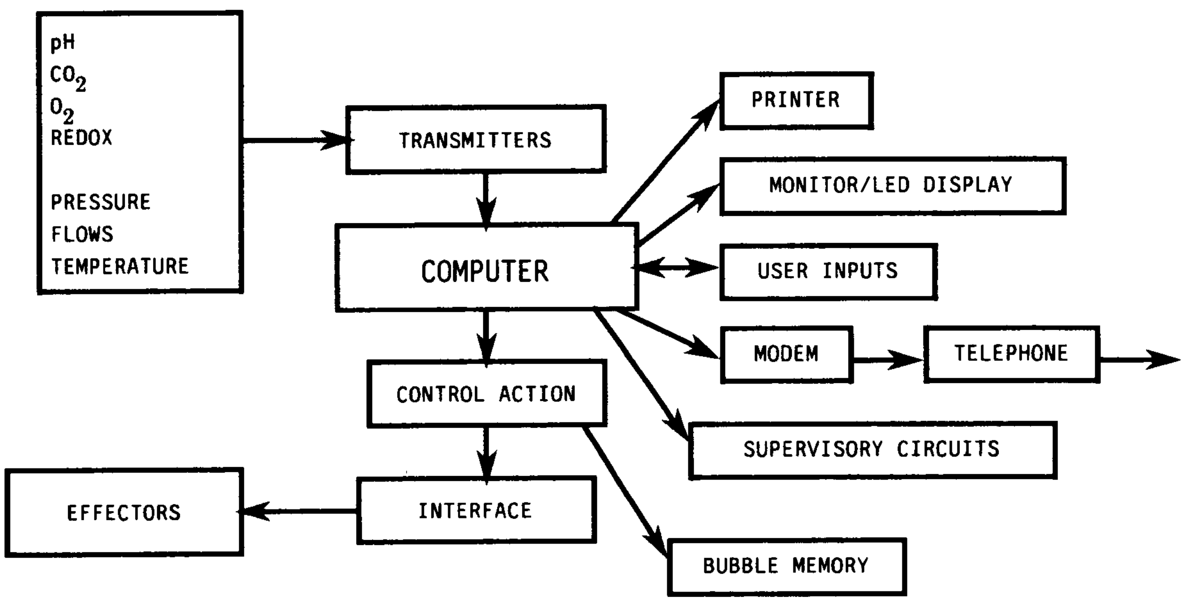


Figure 4-7.- Bioreactor process control computer interfaces.

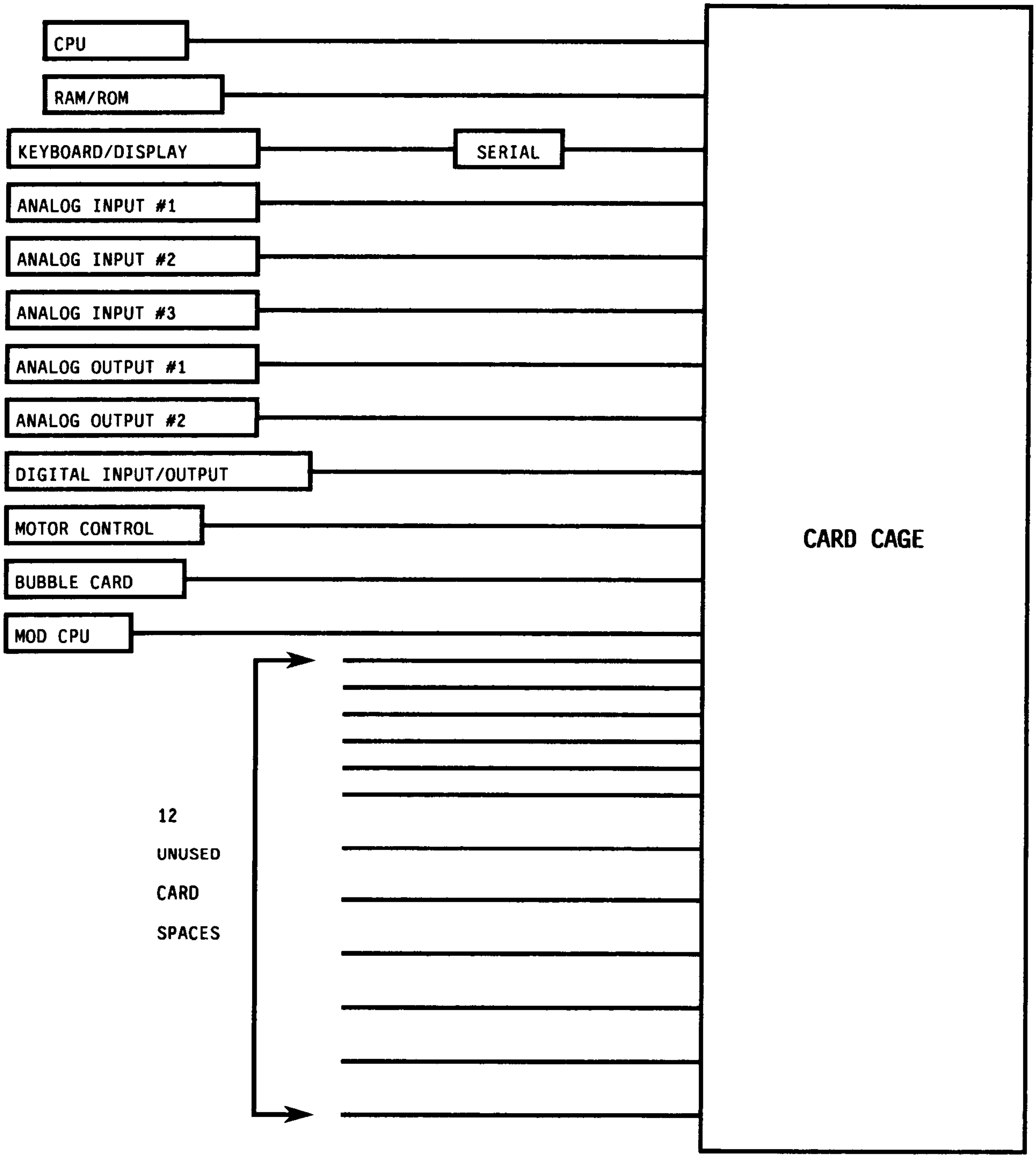


Figure 4-8.- The process controller.

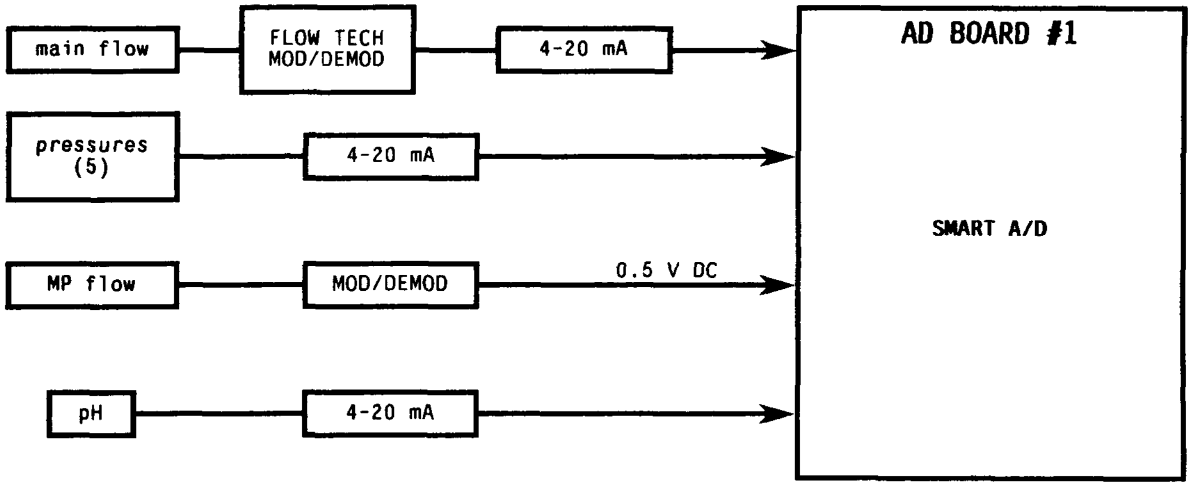


Figure 4-9.- The process controller (continued).

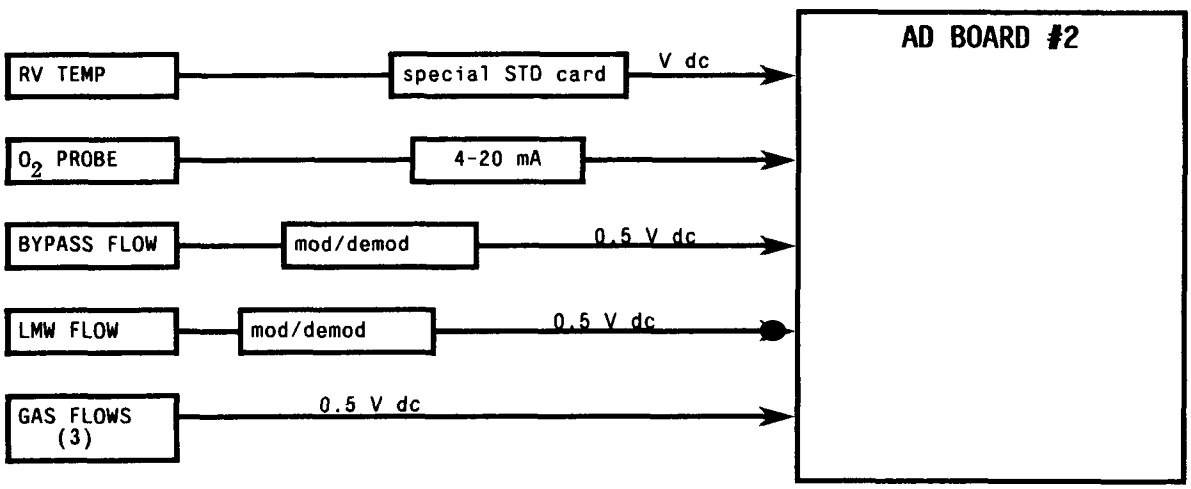


Figure 4-10.- The process controller (continued).

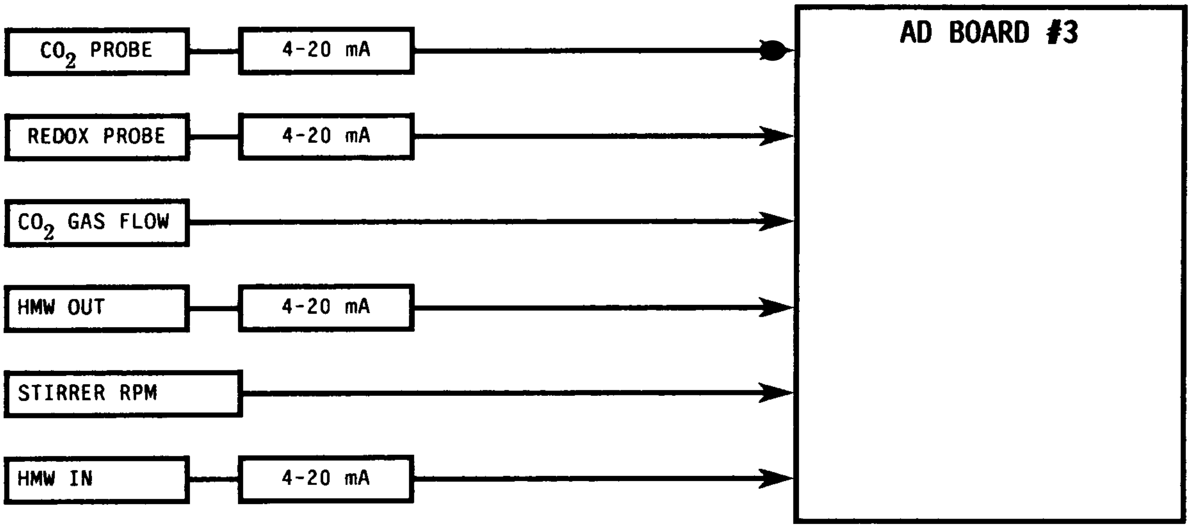


Figure 4-11.- The process controller (continued).

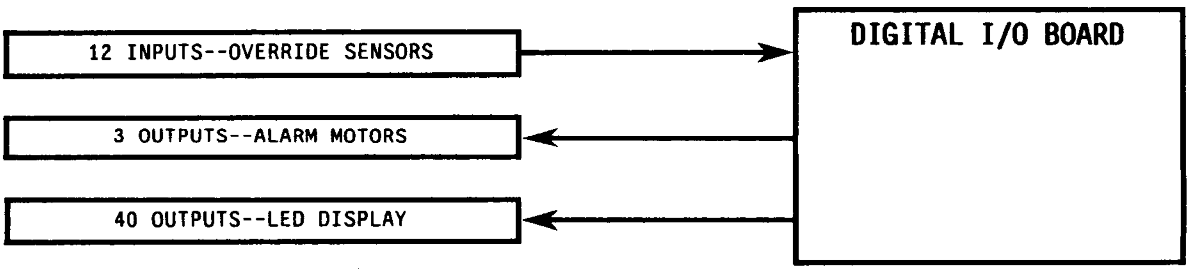


Figure 4-12.- The process controller (concluded).