The Role of the Personal Computer in the Design and Development of Advanced Life-Support Equipment for Tactical Aircraft

Marty Pecaric

Department of Community Health
University of Toronto
Toronto, Ontario

Abstract

Pilots of tactical aircraft are exposed to high accelerative forces. Acceleration in the headward direction (+Gz) will decrease blood flow to the head, causing changes in the visual field and/or loss of consciousness. G-protective life-support systems offer vital protection to the pilot, creating a safer flight environment and improving operational effectiveness. Life-support systems traditionally use mechanically-actuated regulators whose pressure outputs are a function of a single control input. With the advent of solid state circuitry, state-of-the-art hardware manufacturers have begun implementing electronic control algorithms. Multiple control inputs are used to ensure safety, and performance surpasses that of older systems. However, the inclusion of new technologies into the research environment requires the capability to alter critical parameters for the purpose of designing and developing life-support equipment. Consequently, a prototype life-support system (Carleton Technologies Inc.) was modified to allow full control capability using a personal computer (Macintosh). The control computer was configured with high-speed plug-in data acquisition and direct memory access boards (National Instruments). Software (LabVIEW) was used to acquire and process multiple control inputs. Open-loop algorithms allowed independent control of multiple regulators using simple (single input) and complex (multiple input with adaptive loop) control structures. A second personal computer was used to collect and analyze experimental data. This integrated control and data acquisition system proved to be very reliable, provided a high level of flexibility, and substantially reduced costs and turnaround times between successive investigations. The paper will briefly describe the computer life-support-system interface and outline some of the benefits associated with its implementation into the research environment.

1 Introduction

The earth's gravitational field causes an object to fall towards the surface of the planet. The standard rate of acceleration is a constant (g). If this motion is opposed (i.e., if free fall is prevented), the force exerted by the body at rest manifests itself as weight. As the mass of a body remains constant, changes in force can only be achieved by changing the gravitational environment.

Pilots of highly agile aircraft are exposed to a varying gravitational environment when performing maneuvers requiring rapid alterations in direction (for example, during aerial combat situations). Forces acting on the surfaces of the aircraft alter the direction of flight (Figure 1A). According to Newtonian laws of motion, application of a force on a body results in an acceleration proportional to the applied force and inversely commensurate to the mass of the body. For every action, there is an equal but opposite reaction (Figure 1B). Thus, during aerial maneuvering, acceleration replaces the gravitational constant *g*, and inertial forces are produced that are equal but opposite to accelerative forces. The force due to acceleration is usually normalized with respect to the gravitational constant, the measure being the unit G. Hence, a 2G gravitational environment would produce an accelerative force equivalent to twice the earth's gravitational field.

Physiological consequences of an altered gravitational environment are dependent on the direction of the acceleration vector relative to the human body. Acceleration in the headward direction (denoted as +Gz in Figure 1A) produces hydrostatic gradients which affect critical fluid-filled systems. The apparent increase in the weight of the blood during +Gz impedes the heart's ability to pump blood towards the head. There is also a downward displacement of blood towards the legs, which causes significant pooling of blood in the lower body [1]. As the G level is increased, blood pressure falls at head level.

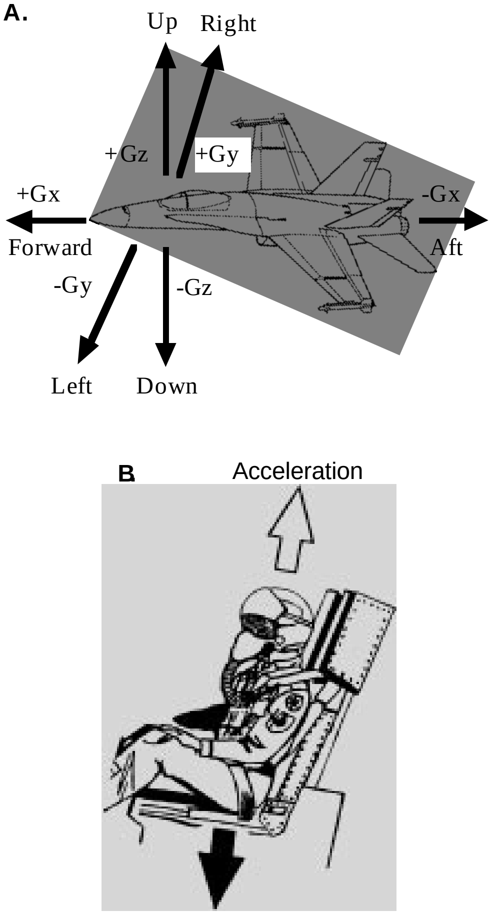


*Figure 1: Alterations in the gravitational environment encountered during aerial combat maneuvering. **A**. Changes in the fight path cause resultant acceleration vectors on the pilot. **B**. For every accelerative force, there is an equal but opposite inertial reaction.*

An unprotected pilot exposed to a +3 to +4 Gz acceleration may encounter changes in the visual field. Visual changes, ranging from loss of peripheral vision to complete blackout, may result. A rapid onset of +Gz may cause loss of consciousness without the preceding visual changes if the acceleration is high enough and is sustained for more than 5 to 7 seconds.

Tolerance to +Gz can be increased with the use of a G-suit and pressure breathing during Gz (PBG). The G-suit consists of five interconnecting bladders enclosed in a fabric shell. The bladders are situated over the pilot's abdomen, thighs, and calves. An anti-G valve (a regulator sensitive to alterations in the +Gz level), pressurizes the lower body garment. Pressurization of the G-suit increases blood pressure, thereby improving tolerance by approximately 1G above a non-protected state [2,3]. Positive pressure breathing requires a modified breathing regulator. The PBG regulator increases the gas pressure in the pilot's oronasal mask in proportion to the +Gz level and is controlled by a pneumatic input signal supplied from a G-suit pressure tap. PBG also increases blood pressure, and can improve G-tolerance by 1 to 3 +Gz, depending on the schedule used [4,5]. However, the amount of pressure required at different +Gz levels from the breathing regulator and G-valve has yet to be standardized. Investigations involving pressure breathing and G-suit pressure schedules must continue before optimal G-protection systems can be implemented in tactical aircraft.

2 Design of Advanced Life-Support Equipment

2.1 Design Variables

Development of life-support equipment can be distributed into three major areas of concern: (1) design of the G-suit; (2) the rate of inflation and the final G-suit pressure at a given G level (i.e., G-valve performance and output schedule); and (3) the positive pressure breathing schedule. All three factors affect the pilot's physiological state and, therefore, alter his tolerance to +Gz (Figure 2). A modification in one design area will have subsequent influences on the remaining two. Consequently, if a better G-suit is introduced, the G-suit pressurization schedule may require adjustment, which in turn could alter the physiological response to PBG. Hence, the optimization of life-support equipment is a multi-dimensional process requiring the tight control of all variables. This optimization is further complicated by the large individual variability between human physiological states and the body's varying responses to environmental stressors.

Yet another complication is introduced by the precarious relationship between design and implementation. A life-support system may provide a high level of G-protection, but may not

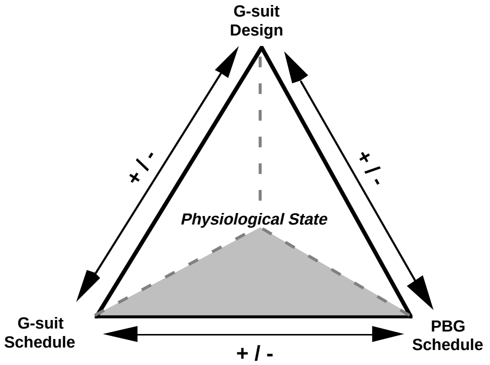


Figure 2: Relationship between the three major areas of research in the design of an advanced life-support system and the pilot's physiological state. Modification of a single parameter (a side in the triangle) influences the protective capabilities of the remaining two sides.

meet specific operational criteria. Cost and pilot acceptance factors (thermal load, mobility, comfort, etc.) may negate large improvements in G-tolerance. A new system must fulfill the end user's demands while still meeting the goals required of protective systems: (1) to create a safer flight environment; and (2) to improve operational effectiveness.

2.2 Past Research Obstacles

Acceleration research in the past used two mechanical anti-G regulators to provide output pressure in proportion to a control input: (1) the G-valve pressure was varied as a function of +Gz and (2) PBG output increased with respect to the input pressure from the G-suit. Redesign and production of prototype pneumatic or mechanically controlled systems with one output pressure schedule based on a single control input were both costly and time-consuming. As a result, investigations were difficult to conduct and long turnaround times between experiments were common. A means with which to rapidly and efficiently control the output pressures from the G-valve and PBG regulator was lacking. Only with the advent of a new generation life-support system could this technological limitation be eliminated.

2.3 Solid State Technology

Electronic breathing regulators and G-valves produce G-suit and PBG pressure schedules from information provided by an internal accelerometer and pressure transducer, respectively. The accelerometer and G-suit pressure transducer supply analog inputs to the system's electronic control unit (ECU). Voltage outputs from the ECU are used to control the output pressures from the PBG regulator and G-valve. Electronic pressure regulating systems have proven to be very reliable, respond rapidly to control inputs, and supply higher air flows to the mask and G-suit than traditional anti-G regulators.

Modifications to the control structure of an electronic life-support system are necessary to provide the flexibility required for acceleration research. A vital component of this system is the controller, a computer used to provide critical status information to the electronic control unit. The status information can be used to generate independent PBG and G-suit pressure schedules. The system can then produce any PBG and G-suit pressure schedule defined by the following parameters: (1) cut-in +Gz level; (2) Δ in pressure / Δ +Gz; and (3) maximum pressure of the schedule (see Figure 3).

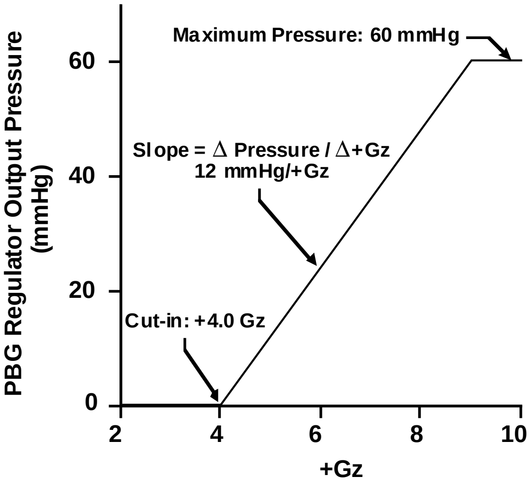


Figure 3: Graphic depiction of a PBG schedule indicating the cut-in, slope, and maximum pressure level.

Generation of external control voltages using a computer has several advantages: (1) the delivery of highly accurate control voltages; (2) the capability to rapidly change voltage inputs; and (3) the ability to simultaneously generate control voltage outputs using information from additional external sources (i.e., pressure transducers, accelerometers, etc.).

With the improved performance of the personal computer and the introduction of plug-in data acquisition boards, a PC-based system can be a viable alternative to a mainframe environment. Such a system was developed in the acceleration research laboratory at the Defence and Civil Institute of Environmental Medicine and interfaced with a modified, electronic life-support system. Open-loop control of the G-valve and PBG regulator was successfully accomplished. A second PC was used to collect system performance and physiological data. Additional software was written to allow rapid interpretation of the results. A brief overview will be provided, along with the benefits associated with the implementation of such a system.

3 The Life-Support System

3.1 The Pressure-Regulating System

PBG and G-suit pressures were controlled using a modified life-support system (Altitude and Acceleration Protection System (AAPS), Carleton Technologies, Orchard Park, NY). The AAPS system (Figure 4) was composed of an electro-mechanical breathing regulator (EMBR), an electronically controlled G-valve, and an electronic control unit (ECU).

The life-support system was configured in such a way that an external discrete input to the system's ECU could be applied via a toggle switch. When a discrete signal was received, the ECU ignored the internal transducer signals and used two externally supplied command voltages (pressure breathing and G-suit pressure) to compute the appropriate microprocessor output signals to the drive amplifiers. The externally supplied command signals were limited so that the respective maximum output pressures from the PBG regulator and G-valve were 90 mmHg (48.18" H_20) and 12 psi (620 mmHg), regardless of the actual command value.

The pressure regulating system was then calibrated. A variable DC power supply was used to determine the pressure delivered by the EMBR and G-valve at different input voltages. Regression analyses were used to formulate equations that were then incorporated into the software control algorithms.

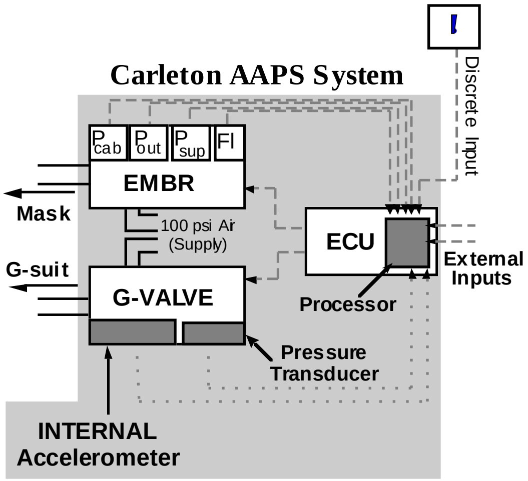


Figure 4: Schematic of the AAPS life-support system. The system was composed of an electro-mechanical breathing regulator (EMBR), an electronic G-valve, and an electronic control unit (ECU). Transducers sensing cabin pressure (P_{cab}), output pressure (P_{out}), supply pressure (P_{sup}), and flow (Fl) were located inside the EMBR. A pressure transducer and accelerometer in the G-valve provided +Gz and G-suit pressure information to the ECU. A discrete input to the ECU via a toggle switch prevented the processor in the ECU from computing internal command schedules.

3.2 Control Inputs and Safety Instrumentation

EMBR and G-valve output were measured as pressures in the oronasal mask cavity (Pmask) and in the G-suit input hose (Pgsuit), respectively, using calibrated variable reluctance pressure transducers (DP-15, Validyne, Northridge, CA). Output from the EMBR also supplied pressure to a counterpressure upper garment worn by the subjects.

Due to an improved signal-to-noise ratio from the Pgsuit transducer, the output from the variable reluctance transducer was used as the control input to the computer instead of the AAPS internal pressure transducer signal. The AAPS accelerometer analog output was not used as the +Gz control input. Installation of the system in the centrifuge required attaching the pressure regulators (G-valve and EMBR) to the side of the gondola seat, which left them lower than heart-level. Correspondingly, the +Gz levels at the G-valve were much higher than nominal heart-level values. The +Gz level was subsequently measured via an external accelerometer (4310-20-AGIM, Systron Donner, Concord, CA) already mounted at the appropriate position on the centrifuge gondola seat (Figure 5).

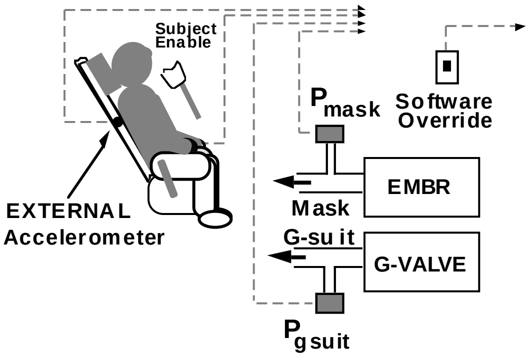


Figure 5: Control instrumentation and subject safety switches. The centrifuge +Gz level was measured using an external accelerometer. Oronasal mask (Pmask) and G-suit (Pgsuit) pressures were monitored using variable reluctance pressure transducers. Two switches, a subject "enable" and a software "override" button, were used to terminate mask and/or G-suit pressurization.

When necessary, the subject was instructed to engage an "enable" switch. This ensured that the computer did not initiate control voltage inputs to the ECU until the subject was ready, and allowed the subject to terminate pressurization of the G-suit and/or mask at any time. A software "override" switch was also available to the system operator. The "enable" and "override" switches provided +5 VDC signals to the control computer. If either switch was disengaged, the output pressures from the life-support equipment were reduced according to criteria designed to provide the greatest protection and comfort to the subject.

4 The Computer Controller

4.1 Instrument Control Configuration

The analog voltages from the "enable" and "override" switches, pressure transducers, and accelerometer were fed to a multifunction board (MIO16H, National Instruments, Austin, TX) of a computer (Macintosh IIX, Apple Computers, Cupertino, CA). A 32-bit direct memory access controller board (NB-DMA2800, National Instruments, Austin, TX) sped up data transfer. Graphical software (LabVIEW, v2.2, National Instruments, Austin, TX) was used to develop a real-time instrument control program.

The hardware/software received single or multiple control input signals and converted the analog data to working units (mmHg, +Gz units, etc.). The pressure schedule parameters for both the G-suit and PBG pressures, including any necessary timed delays in pressurization, were entered by the system operator using the graphical user interface. A clock/timer allowed control of delays in mask and G-suit pressures. Based on information provided by the control input instrumentation (accelerometer, transducers, etc.), subject and system status, the clock/timer, and the PBG and/or G-suit pressure schedule parameters, the required mask and G-suit pressures were calculated. The pressures were then converted to the necessary control voltage inputs to the ECU (Figure 6). The control voltages were supplied by the multifunction board to the AAPS system. Figure 7 is a schematic representation of the integrated system.

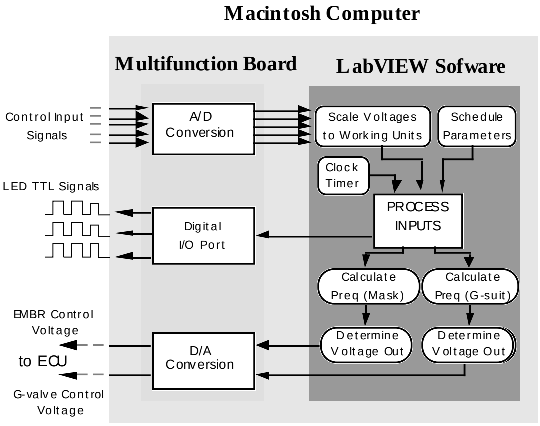


Figure 6: The multifunction board and LabVIEW software environment of the control computer. Analog voltages were acquired by the multifunction board, converted to working units, and used to calculate the required mask and G-suit pressures. The resultant control voltage was then supplied to the ECU.

4.2 Graphical Control Interface

Using LabVIEW, a graphical user interface was developed to allow the computer operator to specify the type of control signals supplied to the computer (e.g., external accelerometer or pressure transducer) and the parameters of the pressure schedules. Part of a front panel display is shown in Figure 8. In this figure, the control signal is provided by the external accelerometer

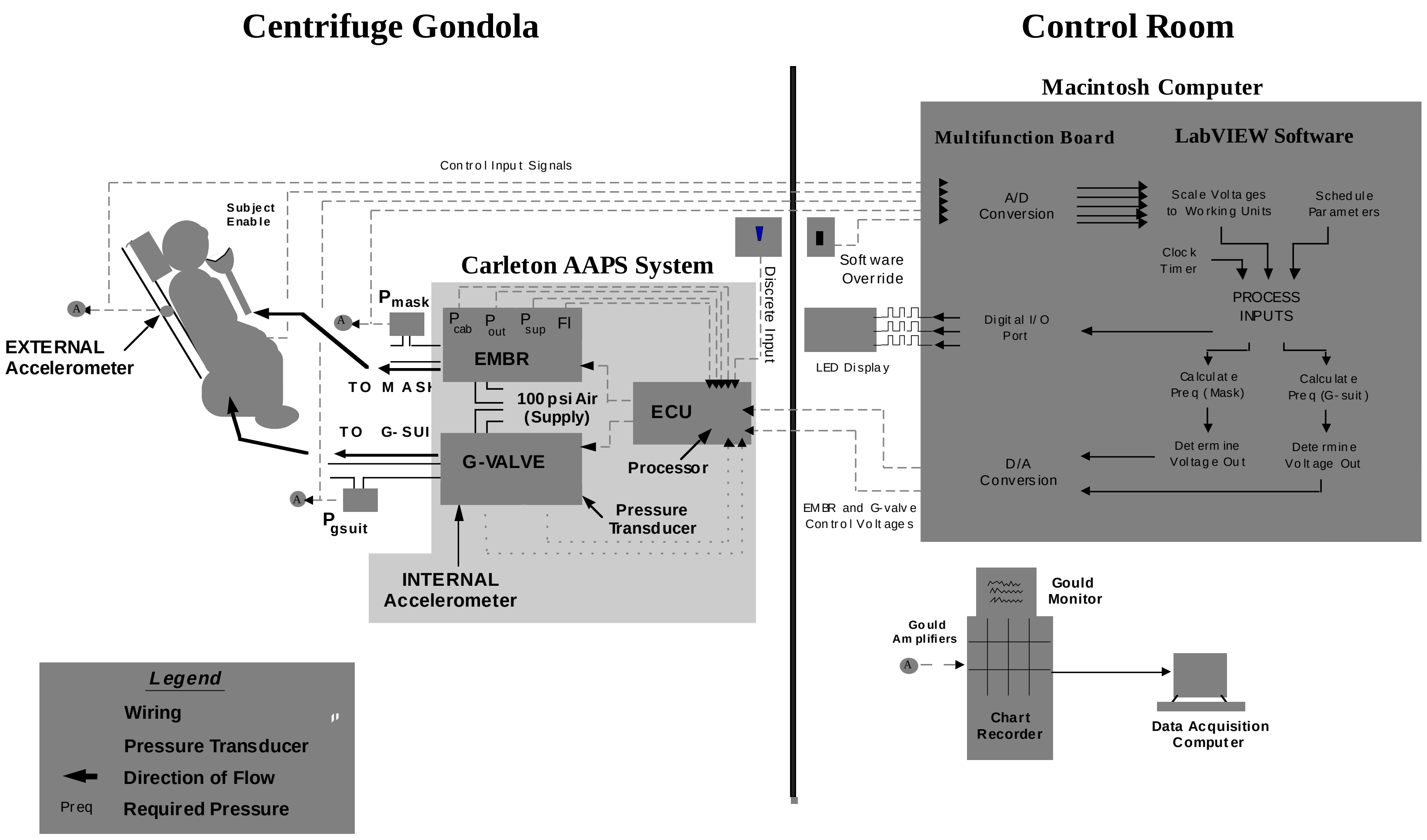


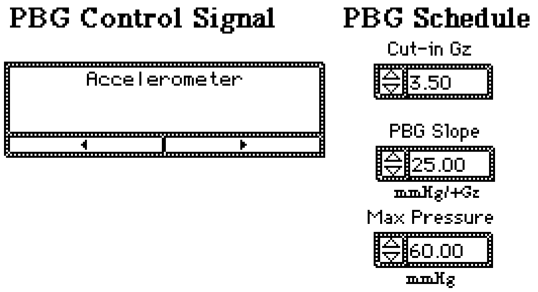
Figure 7: Schematic representation of the computer-controlled pressure-regulating system.

($+Gz_{(accel)}$). Pressure breathing begins at +3.5 Gz, increases by 25 mmHg / +Gz, and can reach a maximum level of 60 mmHg. The equation for the required mask pressure ($Pmask_{(req)}$) as a function of +Gz would be:

$$Pmask_{(req)} = (+Gz_{(accel)} - Gz_{(cut\text{-}in)}) * Slope$$

where: $0 \le Pmask_{(req)} \le$ Maximum Pressure

The computer operator could change any of the front panel digital controls with a mouse. This facilitated alterations in any schedule parameter and allowed rapid selection of a PBG control signal. The number of digital controls could be increased and decreased, so any arbitrary function could be generated.



PBG Control Signal

Accelerometer

PBG Schedule

Cut-in Gz 3.50

PBG Slope 25.00 mmHg/+Gz

Max Pressure 60.00 mmHg

Figure 8: Front panel of the graphical user interface showing the digital controls used by the operator to specify the type of control input to the computer and the pressure schedule parameters. The schedule parameters and the acceleration data are then used by the software to calculate the required output pressure.

Though traditional schedules invoke a linear increase in pressure as a function of a single control input, multiple control inputs and numeric constants can be used to generate complex nonlinear (i.e., output not directly proportional to input) pressure profiles.

4.3 Simple and Complex Control Structures

Inputs from any number of secondary controllers were delivered to the data acquisition board and then converted to working units, thus allowing the use of arbitrary control inputs to generate various pressure schedules. Figure 9 demonstrates the improved flexibility associated with this type of approach. Nominally, the pilot's G-suit is pressurized by the G-valve as a function of the +Gz level (Figure 9A). In the research environment, traditional equipment severely limits procedural options. Using a computer controller, the primary control input (+Gz in Figure 9A) can be replaced by a single arbitrary input (Figure 9B) or can be part of a complex multiple control system that implements an adaptive loop (Figure 9C). Consequently, any PBG and G-suit pressure can be generated, either independently or dependently, using single or multiple inputs.

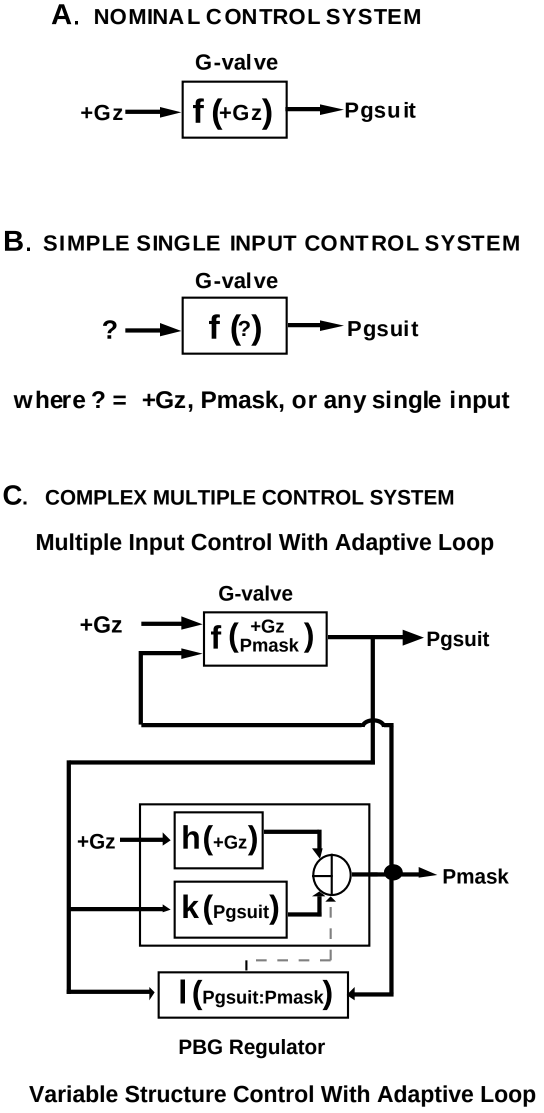


*Figure 9 Block diagrams illustrating different control loop structures. **A**. The nominal control input to the G-valve is +Gz. Output (Pgsuit) is a function of the input signal and is defined by fixed G-suit schedule parameters (cut-in, slope, and maximum pressure).*

Only one output pressure schedule is provided by this type of control system. ***B****. Computer control improves flexibility. Schedule parameters can be altered such that any output pressure can be generated using an arbitrary control input (+Gz, Pmask, etc.).* ***C.*** *Adaptation of a complex control loop. G-valve output is a function of both the +Gz level and the mask pressure (the output from the PBG regulator). Output from the PBG regulator is nominally controlled by a single input function* ***h****, but follows a function of G-suit pressure,* ***k****(Pgsuit), if the ratio between G-suit and mask pressures (****l****) is less than a predefined value. The ability to switch from one function to another defines this type of control as a variable structure control. The use of the output variable in the switching algorithm describes an adaptive control loop as part of the system.*

4.4 Secondary Control Tasks

The control computer could also be used for a variety of secondary control tasks. Transistor-transistor-logic (TTL) compatible digital outputs from the multifunction board and audio outputs from the control computer could also be programmed using LabVIEW. Respective outputs were used to illuminate LEDs for visual display of the system's status and to provide an auditory warning when necessary.

To further increase research flexibility, analog outputs could also be used to control other systems located inside the centrifuge or as event markers for streamlining data analysis protocols.

5 Data Acquisition and Analysis

When conducting acceleration research studies, a large number of centrifuge profiles are used to test various components of the life-support system. The data must be collected and reduced in a way that allows the information to be statistically analyzed and plotted. Collecting the data on a computer increases signal resolution, but it may also complicate data reduction. Implementation of software capable of reducing a large data file into a workable format quickly and efficiently minimizes the complications incurred with digital data recording.

5.1 Data Collection

Physical and physiological data for manned and unmanned centrifuge runs were collected on a second personal computer (Macintosh IIci, Apple Computers, Cupertino, CA). The computer was configured with a 12-bit analog-to-digital board (MIO16H, National Instruments, Austin, TX) and LabVIEW software (National Instruments, TX). Sixteen single-ended signals could be collected at sampling speeds of 200 Hz. Two channels of data were continuously displayed to the investigator. Gain settings for each channel could be set independently using the graphical user interface. The data, in voltage units, was stored as one contiguous multiplex file on the recording computer.

5.2 Analysis Software

Upon completion of an experimental series, the computer operator invoked a software routine specific to the data reduction requirements. The operator selected the appropriate data file. The data file was demultiplex, scaled to working units, and converted into text format. Using rule-based algorithms, event markers were located on specified data channels. LabVIEW subroutines could then called to perform statistical analyses (means, standard deviations, etc.), decimate data, and perform mathematical operations. The ASCII output of the analysis was saved in spreadsheet format, allowing easy portability into statistical analysis and plotting packages.

Development of rule-based analysis software has proven to be an efficient alternative in acceleration research projects that follow repetitive, invariable protocols. Such software was not only of time-saving importance in this project, but its merits in removing experimenter bias and error further justified its utilization.

6 State-of-the-Art Technology in the Research Environment

The integration of a life-support system with a computer could not have been accomplished without the recent advances in technology. The software development package (LabVIEW) was integral to the rapid formulation of the interface. The software provided many advantages: (1) its ease of use and fundamental graphical user interface was an important asset for both programmer and computer operator; (2) extensive libraries of functions and subroutines reduced software development time; and (3) the modular construction of the software enabled quick modification of existing code.

An electronically controlled life-support system, capable of receiving multiple external control inputs, was previously unavailable to the acceleration research community. A close working relationship with industry brought about the creation of a system compatible with both operational and research requirements.

The merger of industrial expertise with research requirements led to the development of a life-support system capable of meeting the stringent operational and investigative requirements. The system ensured various degrees of safety to the subject using both electromechanical and software engineering principals. If the subject, investigator, or computer operator was not satisfied with the applied PBG and/or G-suit pressure, pressurization was quickly terminated using the appropriate software "override" switch. Thereby, even with a computer failure, the subject could not receive high levels of mask and/or G-suit pressure.

7 System Benefits to Research

The introduction of the personal computer into the acceleration research environment has proven to be a valuable resource in the development of advanced life-support equipment. This paper could not begin to detail all the applications and uses of the PC in this area.

The benefits of introducing state-of-the-art technology into the acceleration milieu were shown in the rapid development of an advanced life-support system for the CF-18. A large number of diverse experimental procedures were required to accomplish this task. Time constraints necessitated rapid turnaround times between successive experiments. Results from the 8 different experimental protocols conducted over a 9-month period (involving more than 1400 manned +Gz exposures) validated the usefulness and safe operation of the computer-controlled life-support system. The limitations imposed by traditional equipment would have restricted the number of investigations performed, decreased the research capability, and delayed completion of this critical investigative focus.

8 Conclusions

A computer interfaced with an electronic life-support system was found to provide a means of generating PBG and G-suit pressure schedules based on single or multiple control inputs. Research potential was further improved by a second PC configured to collect and then analyze experimental data. The integrated system forms the basis of a unique research tool that supports the complex requirements associated with acceleration protection research.

Acknowledgments

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References

1. R.W. Krutz, R.R. Burton, and E.R. Forster, "Physiologic correlates of protection afforded by anti-G suits," *Aviat. Space Environ. Med.* 61, 1990, pp. 106-111.
2. R.R. Burton, M.J. Parkhurst, S.D. Leverett Jr., "+Gz protection afforded by standard and preacceleration inflations of the bladder and capstan type G-suits," *Aerospace Med.* 44, 1973, pp. 488-494.
3. E.H. Wood, "Development of anti-G suits and their limitations," *Aviat. Space Environ. Med.* 58, 1987, pp. 699-706.
4. J. Maloan, M. Pecaric, and F. Buick, "PBG schedules and +Gz-tolerance: II. ROR profiles and effects of PBG cut-in, slope, and maximum pressure," *Aviat. Space Environ. Med.* 64, 1993, p. 450.
5. J.M. Clère, D. Lejeune, D. Tran-cong-chi, H. Marotte, and J.L. Poirier, "Effect of different schedules of assisted positive pressure breathing on G-level tolerance," in *Proceedings of 26th Annual SAFE Symposium*, Las Vegas, Nevada, 1988, pp. 76-79.

Biography

Marty Pecaric is completing his final year of PhD studies in Community Health at the University of Toronto. In addition to his academic endeavors, he is a contractor at the Defence and Civil Institute of Environmental Medicine. He has 7 years of aerospace research experience, specializing in both high-acceleration and high-altitude protective systems. His other area of interest is Space Life Sciences. He was a co-investigator in an International Micro-gravity Shuttle Mission experiment, and is currently involved in the development of an advanced G-protection system for the Canadian Forces F-18. Mr. Pecaric is a member of the SAFE Association, the Canadian Aeronautics and Space Institute, and the Canadian Aerospace Medicine Society.