Servo-Control of a Pneumatic Motion Platform For Use as a Low Cost Simulator

by

Keith J. Breinlinger

B.S. Mechanical Engineering.
Massachusetts Institute of Technology, 1996

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

The project called for the design and development of a motion platform that would enhance the home game player's experience. The design had to be safe, easy to use, inexpensive, yet still effect realistic motion cues to the user.

The design consists of an upper platform coupled to a base by three pneumatic bladders. By controlling the airflow into these bladders, the upper platform can be made to pitch, roll and heave. The motions of sway and surge are simulated by angular motions in roll and pitch, respectively. This simulation platform is connected to a personal computer with a motion control board. A universal output is proposed that would promote a "plug and play" system that could be utilized for all types of motion platforms and feedback devices. The motion platform would therefore act as a slave, receiving master commands from various software games.

Thesis Supervisor: Alexander Henry Slocum
Title: Alex and Brit d'Arbeloff Associate Professor of Mechanical Engineering

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1. Introduction

This thesis encompasses the entire design process from a vague unformed and unresearched idea to an alpha prototype. Plans for a beta prototype and areas of improvement are discussed but not fully developed. Once the beta prototype is complete, plans for low scale production can begin. The low scale manufacturing and marketing of the system is also considered. The design is carried out by means of a step by step process.

First, a need was recognized, a need to improve the realism in home simulation video games. At the time of conception, there existed a great variety of multimedia products designed to enhance a game player's experience. These included racing car steering wheels, realistic fighter joysticks, head mounted displays and other input and output devices. However, there was nothing on the market that actually provided motion or motion cues to the player. Motion platforms exist for the training of pilots but these typically cost upwards of one million dollars. Thus, there exists a need for a low cost motion platform to be driven by a home PC.

The initial idea was to use a hexapod, or Stewart platform, to simulate all six degrees of freedom. To be low cost and consequently, available to a home user, pneumatic cylinders seemed like ideal actuators. With this idea in mind, the design work began. As mentioned earlier, a design process was followed using the following steps.

1) Problem Definition
2) Concept Generation
3) Concept Selection
4) Layout
5) Embodiment (Alpha Prototype)
6) Beta Prototype & Manufacturing Plan
7) Production Ramp-up
8) Full-Scale Production

As mentioned earlier, the scope of this thesis is from Step 1 to Step 5. Steps 6 through 8 are considered but not executed. Before the problem was fully defined, some background research needed to be done such that a more precise problem definition could be arrived at.

2. Background

Commercial and military flight simulators are very expensive and require dedicated computer systems. These simulators range from quarter million dollar systems with three degrees of freedom, to multi-million dollar centrifuge designs. High end flight simulators tend to take one of two approaches: a hydraulic six degree of freedom motion platform (Figure 1) or a centrifuge type utilizing four axes (Figure 2) or more.

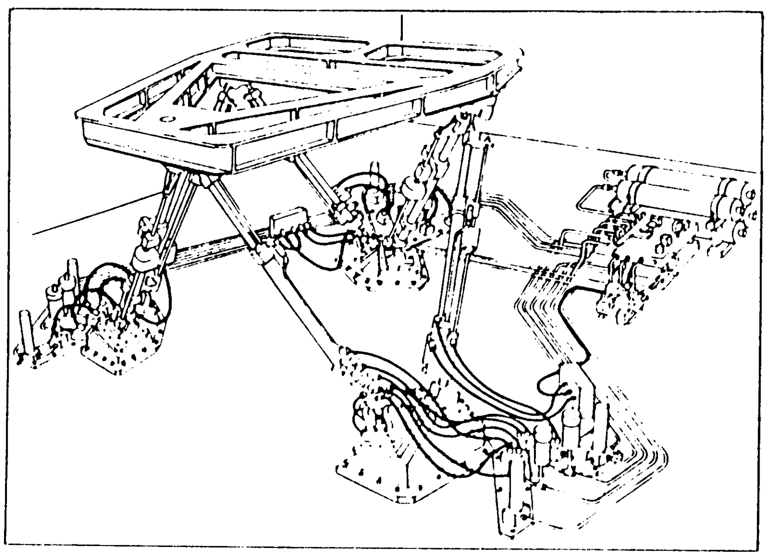

FIGURE 1 - SIX DEGREE OF FREEDOM, STEWART PLATFORM HIGH-END SIMULATOR

One of the inherent problems with the 6 DOF (Degree Of Freedom) platforms is they have a finite travel length and cannot reproduce sustained linear or angular accelerations. This necessitates the need for washout filters that attenuate the real or desired accelerations to motions that can be reproduced on the finite travel simulator. Thus, the user cannot experience true sustained accelerations, but with the right filters and significant travel lengths the accelerations can be reproduced in manner which closely resembles the actual movements. When combined with visual motions, these movements can effectively fool the human body's sensors. The goal of any well-designed simulator is to provide the user with an experience as close to the real life situation as possible.

The centrifuge type simulator can reproduce sustained accelerations by rotating continuously about the axis perpendicular to gravity and then orienting the user at the end of this large swinging arm.

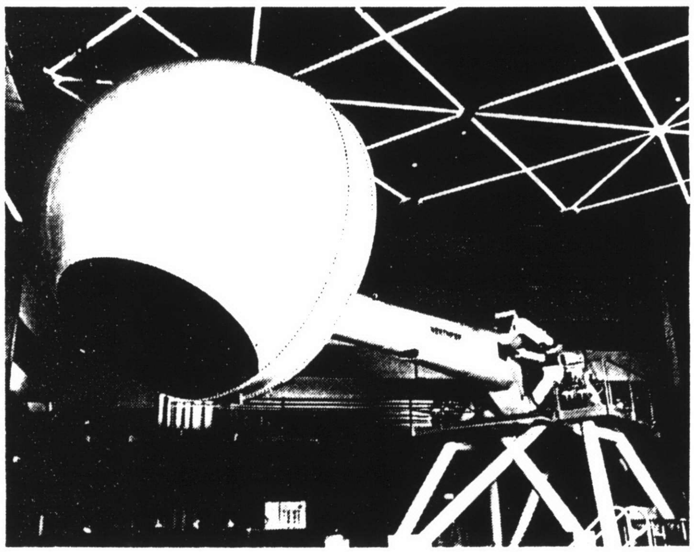

FIGURE 2 - FOUR DEGREE OF FREEDOM, CENTRIFUGE TYPE HIGH-END SIMULATOR

This simulator can be very effective but it requires a very large motor to swing the arm around and also a tremendous amount of floor space. It also needs to be walled off so that no one walks in the way of the swinging arm. These simulators usually start at prices above ten million dollars per unit.

For short accelerations, most Stewart platforms can produce a true forward acceleration, however, when a long acceleration is required or the simulator does not have a forward motion, other methods must be used. When a human body undergoes a forward acceleration many things change which the body's sensors take note of. One of the most noticeable effects of acceleration is the increased pressure on the back and buttocks. Other effects include:

- Decrease in pressure on the seat and lap belts
- Angle of the hips, knees, shoulders and elbows changes slightly
- Seat appears to become harder as more force is transmitted through the lower body
- Eye-point sinks slightly
- Blood pools in the legs
- Inner organs are deformed and the muscles tense to counteract
- Change in the acceleration noted by the vestibular organs

A G-seat attempts to reproduce the effects of acceleration and recreates all but the last three effects[1]. A G-seat is divided into an upper and lower portion. One half supports the buttocks and the lower back, while the other section supports the rest of the back and the head. A G-seat typically uses a hydraulic cylinder which brings these two parts together to recreate a heave motion cue (Figure 3.)

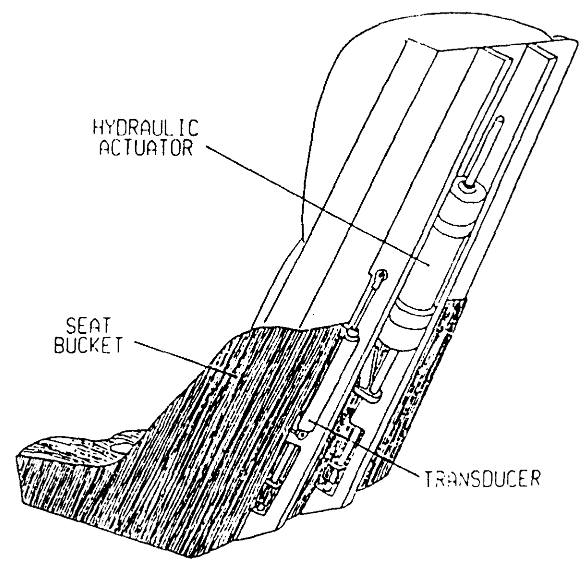

FIGURE 3 - G-SEAT FOR SIMULATION OF SUSTAINED FORWARD ACCELERATIONS

This motion tends to squash the body into the seat thus increasing the pressure on the back and buttocks. This effect when combined with visual cues tends to produce a realistic feeling acceleration. White's research at RAE Bedford concluded that the G-seat provided excellent cueing in helicopter simulations of turns, pull-ups, and bunts. The seat was ineffective at conveying sustained accelerations as there was no distension of the stomach. With the addition of some vibration, however, the pilots were less able to dismiss the cues of the G-seat for sustained accelerations. Thus, a G-seat is a valuable addition to the realism of the simulator but is much more effective when coupled with vibrations.

Another method to make the body perceive acceleration is to simply tilt the body backwards. The gravity vector is then directed to pull the body both into the seat and down and thus this also creates a sensation that can effectively mimic forward accelerations. The tilting motion effects the vestibular organs and the internal organs in the body, but does not create many of the other effects a G-seat can create. Other seats use inflatable bladders underneath the user that can be inflated to higher pressures which hardens the seat.

Another method loosens the seatbelt around the user. During acceleration, the body is forced into the seat and thus the body moves away from the seatbelts. This decrease in pressure on the front of the body can be recreated by using a motor to control the tension in the belt. This would produce a motion cue that is felt during acceleration. The motor could also be used for ensuring proper seatbelt tensioning. The motor could also increase the tension to effect the feelings of deceleration. This would be relatively low cost and might nevertheless be necessary for safety purposes. There are still other methods to produce acceleration cues, but they all use some type of actuator to change the pressure on the body and thus produce a feeling like acceleration. Most of these methods may also be reversed to produce the effect of deceleration. A very effective combination would be to use a G-seat and a tilting back of the seat; this would simulate almost all of the effects the body undergoes in true accelerations. Many simulators use large projection screens or multiple monitors to simulate the large windows that most vehicles have. The importance of visual cues should not be underestimated. In a fully enclosed box with no motion and a good visual system (stimulating the peripheral vision) the body will tend to believe it is actually accelerating. This effect may be experienced while in a stationary plane or train and looking out a window in which another plane or train is in motion. This confuses the body because the visual system perceives motion but the inner ear does not. In such a case, the visual system is usually dominant and motion will be perceived

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[1] White, A.D. "G-seat Heave motion Cueing for Improved Handling in Helicopter Simulation."

for a short duration. Further, the human visual system is tuned to notice objects in motion more than stationary ones. This effect can be seen when viewing a large and diverse scene, the eyes tend to focus on moving objects. This is especially true in peripheral vision in which an object may not be given attention until it moves, and then the head is turned to look at it. For this reason, providing a large wrap-around-viewing area, in which the peripheral vision is stimulated by objects moving past it, can be remarkably effective at simulating motion. Another way in which to stimulate the peripheral vision is to use VR glasses. These would be quite effective and would allow virtual windows of any size. Unfortunately, the state of the art VR glasses are very expensive and the resolution is inferior in comparison to typical monitors. In a study done by Borah, Young and Curry in 1979, they tested the perception of the human body to yaw motion using three different tests. In the first test, only visual cues were used and the users perceived motion was calculated. This was repeated again with only inertial cues (no visual cues) and finally with both visual and inertial cues. The results are shown below.

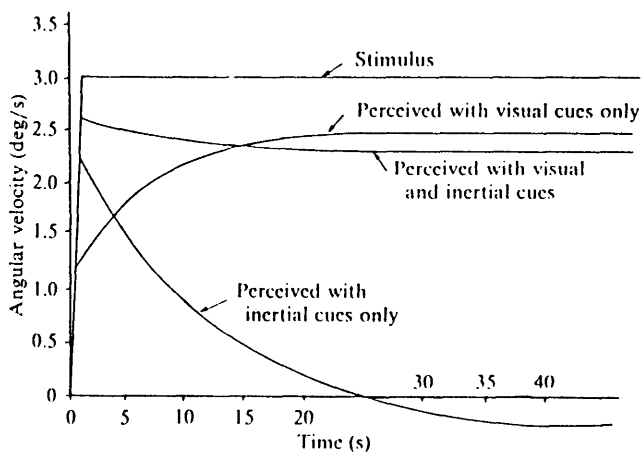


FIGURE 4 - PERCEPTION MODEL RESPONSE TO VISUAL AND INERTIAL CUES IN YAW

Because the body uses multiple sensors, faking motion by only visual cues can make some people nauseous. Providing more motion cues such as increased pressure on the back or tilting the body back can alleviate this problem. In this way the inner ear and pressure sensors also "feel" acceleration and thus more of the body's sensors are in accord and fewer people will get sick.

The human perception of motion is the basis for all motion system and since it is not a perfect system, analyzing the way in which the human body perceives motion has been an intensively researched area. The body uses a host of different sensors to estimate the acceleration and orientation the body is in. The signals from these sensors are received by the brain, which then attempts to determine the state it is in. A basic model is outline below.

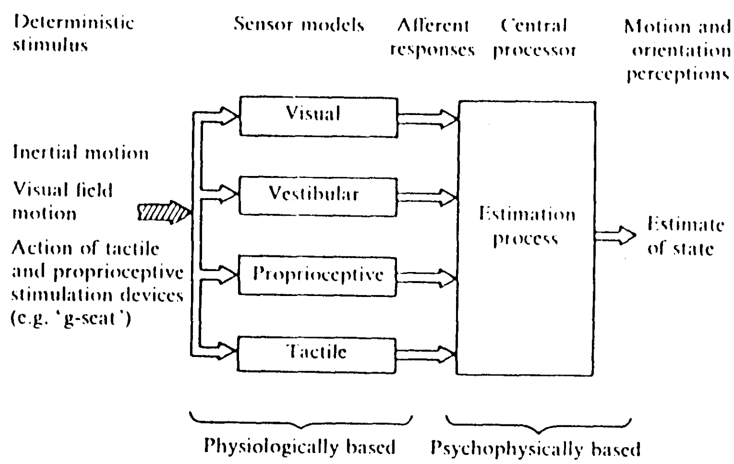


FIGURE 5 - BASIC STRUCTURE OF HUMAN MOTION AND ORIENTATION PERCEPTION MODEL.

From this research, a number of things have been learned which can aid in the development of effective motion simulation systems. The human visual system seems to dominant for low frequency motion and the other sensors dominate for higher frequencies[2]. The three semicircular canals in each inner ear are like damped angular accelerometers and can detect motion as low as 0.1 degree/s^2. These canals are filled with fluid and obstructed at one end by the cupula. The cupula is a gelatinous mass imbedded with hair cells that are sensitive to deformation in one direction. When the canal is accelerated about its axis of symmetry, the endolymph fluid applies a force to the hair cells which causes neurons to send signals to the brain. Also in each inner ear are two otoliths that are responsible for detecting specific force as low as 0.02 m/s^2. The utricular

[2] Rolfe, J.M. Flight Simulation

and saccular otoliths are similar the canals, except the otoliths contain calcium carbonate crystals and thus, when the specific force changes, the crystals move relative to the endolymph causing a deformation of the hair cells. There is no way the sensors in the body can distinguish static body tilt from linear acceleration without the use of the visual system. This is illustrated below.

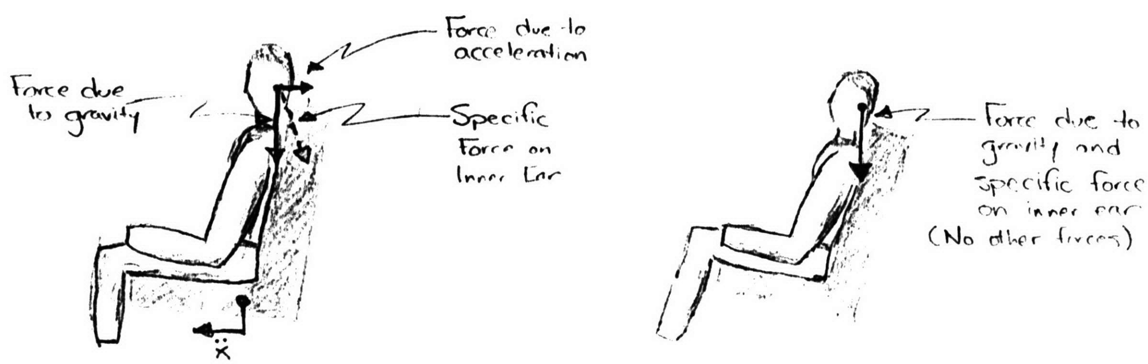


FIGURE 6 - FREE BODY DIAGRAM OF STATIC BODY TILT VERSUS LINEAR ACCELERATION.

The resolution of the otoliths is about 2 degrees of static body tilt. Because both the otoliths and the semicircular canals are located in the head, head motion is sensed regardless of body position. However, there are a number of proprioceptive sensors that detect changes in the body such as tendon length, muscle tension and joint orientation[3]. This information can tell the brain the position of the head relative to the rest of the body as well as noting changes in the forces applied during acceleration.

An effective flight simulator needs not only provide both visual and motion cues but also other effects to enhance the realism of the simulator. A good surround sound system that uses Doppler effects can dramatically increase the realism. The gauges and input

[3] Brown, Y.J., F.M. Cardullo, J.B. Sinacori. "Need Based Evaluation of Simulator Force and Motion Cueing Devices."

devices can also have a dramatic effect on the overall effectiveness of the simulator. The elements of a simulator must work together to create a convincing reality.

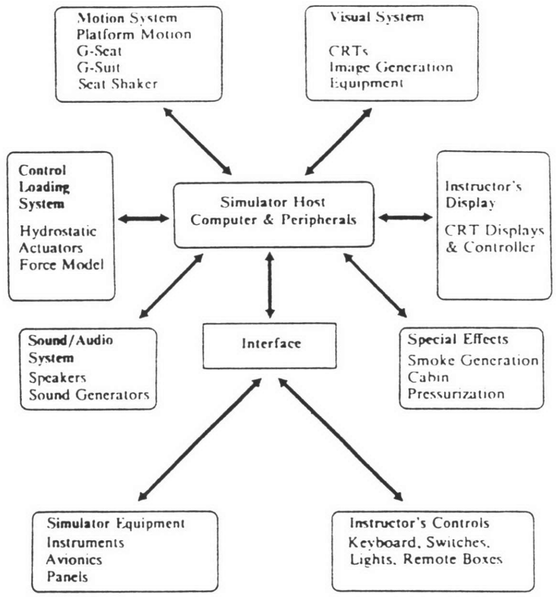
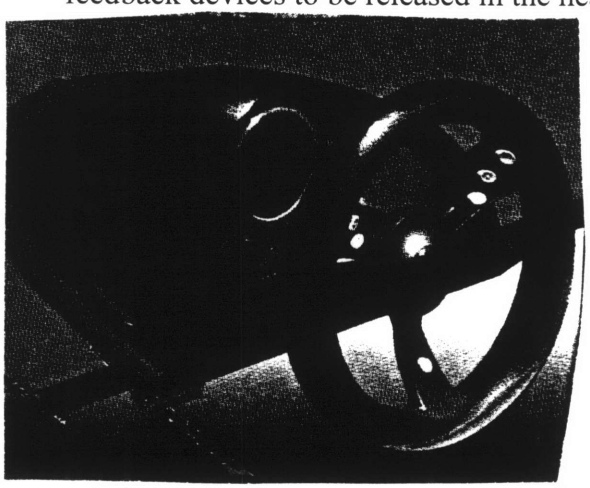


FIGURE 7 - ELEMENTS OF A MODERN FLIGHT SIMULATOR.

High-end simulators also have flight sticks that are able to provide force feedback. These sticks provide a higher resistance to movement when the simulator is turning sharply as compared with an easier turn. This added feature provides a very convincing realism to the user. Fortunately, manufacturers of commercially available joysticks are venturing into this area. At the E3 (Electronic Entertainment Expo), ACT labs, Thrustmaster, CH Products, Microsoft, and Advanced Gravis introduced new force-feedback devices to be released in the near future.



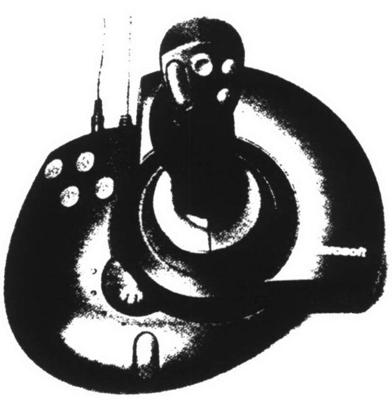


FIGURE 8 - FORCE-FEEDBACK DEVICES: ACT-LAB'S DRIVING WHEEL AND MICROSOFT'S JOYSTICK

Many simulators also have gauges, lights and switches that would be found in a standard cockpit that actually function as they would in the vehicle that is being simulated. Only two manufacturers (Saitek and Quickshot) currently produce devices (for the PC) which takes the place of some of the keyboard keys (Figure 9).

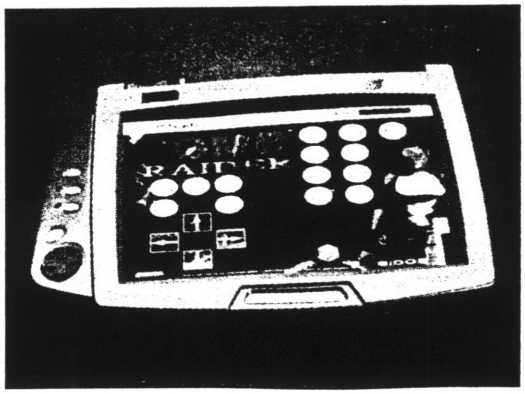


FIGURE 9 - COMMERCIALLY AVAILABLE BUTTON EMULATOR: SAITEK PC-DASH

These keys which might do such things as turn on power, arm rockets, or any other command desired by the user. This adds to the realism but is not as realistic as the dedicated simulators. As the virtual reality and simulator market grows, more companies are apt to join in and develop new and better products that more closely resemble the actual vehicle buttons, switches and dials.

The motion platforms that are available for the home PC are very limited in number and do not provide realistic motion cueing. The Thunderseat and Rock 'n' Ride are two examples of platforms designed for the home PC. More information on PC motion platforms can be found in Appendix A. The Thunderseat does not provide any actual motion other than enhanced vibrations. The Rock 'n' Ride provides motion in response to joystick movements (not software) and has only pitch motions. Therefore, there is no difference in response between a Cessna and an F-18 Hornet. Further, it can be seen below, that this is not an enclosed system so much of the motion cueing will be lost on the user. Because the system does not use a throttle, there can be no true motion cueing for accelerations by tilting the seat back.

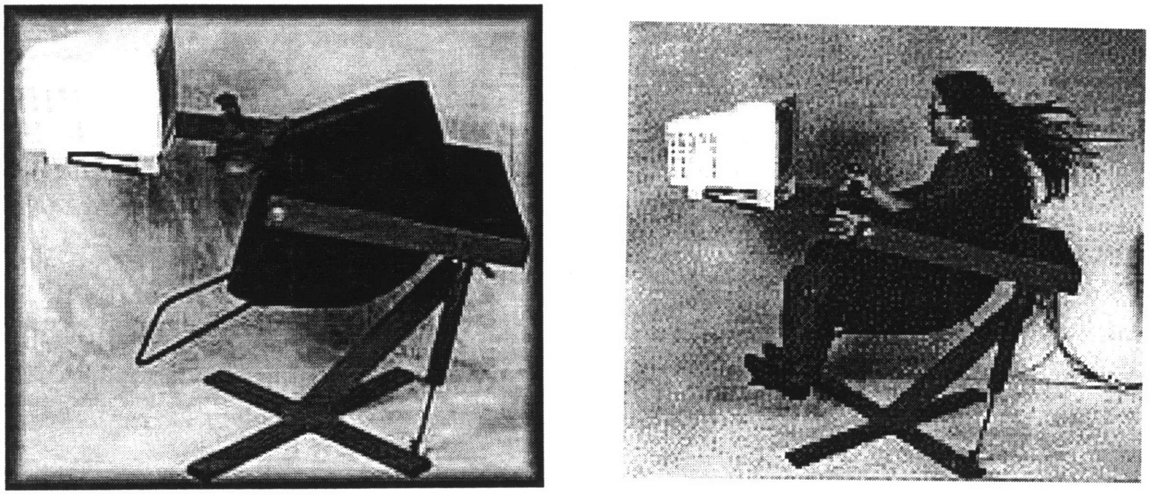


FIGURE 10 - ROCK 'N' RIDE: PITCH AND ROLL PC-BASED OPEN SIMULATOR

3. Problem Definition

Initially, the idea for this project was to place a chair on a Stewart platform (Figure 8) and thus simulate the motion in all six degrees of freedom. The chair should cost less than $5000 and provide a significant improvement in the realism of the simulation games.

Before the system was built, the problem to be solved had to be defined precisely. The initial idea already included an embodiment of the device to be made. That idea was useful for later stages of the design process, however at the problem definition stage, it is best to forget about any preconceived solutions. If one has a solution in mind when drafting the problem definition, one will effectively eliminate all other possibilities. For example, a problem definition might be "A virtual reality simulator utilizing a hexapod configuration." This definition would eliminate such other possibilities as a centrifuge design or a more limited motion simulator. One must decide exactly what purpose the device should fill and then invent or discover an effective means to that end. The solution in mind may or may not be the optimal means to that end. After some background research, the different needs for the project were quantified as a list of requirements. It is helpful to consider not only what requirements are feasible now, but also what requirements might be useful in a few years time. Thus the table (Functional Requirement List) on the following page is grouped into three distinct groups: goals for the project at the present time, in the near future and in the far future. For the present, the major requirements were low cost, safety, and realistic feeling motion. A theoretically ideal system is also proposed for the present, near and far future shown in Table 3. With the functional requirement list as a guide, a problem statement was formed: "A low cost simulator to effect realistic feelings of motion to a human seated in the simulator."

Functional Requirements for VirtuaRide Project				
	Now	Then	Wow	Dominant Physics
Cost	Sell for less than $15000	Sell for less than $10000	Sell for less than $5000	(# of axes)*
	Mfg for less than $10000	Mfg for less than $5000	Mfg for less than $3000	(actuator cost + controller cost/axis)
Motion	Operate at at least 1 Hz	Operate at 10 Hz (for small motions)	Can simulate sustained accelerations in heave.	Limited travel in heave, vert and sway
	3 DOF (Pitch, Roll, Yaw)	4 DOF	6 DOF	Possible unlimited travel in rotations
Motor force	For vertical 1 G acceleration:			F=ma
per axis	220 lbs	300 lbs	400 lbs	M=(mass of person + mass of platform)
Acceleration	1 g in vert, sway and heave 1.5 rad/sec^2 in pitch and roll	1.5g's in vert, sway and heave 2.5 rad/sec^2 in pitch and roll 1.0 rad/sec^2 in yaw	2g's in vert, sway and heave 3 rad/sec^2 in pitch and roll 2 rad/sec^2 in yaw	F=ma 2g's is max accel. for home use without serious safety issues.
Distance to move	10" in vertical motion	15" in vertical motion	20" in vertical	Actuator length
	20° in pitch and roll	30° in pitch and roll	6" in sway and heave	Layout of attach points for
		360° in yaw	30° in pitch and roll	actuators on motion platform
			360° in yaw	and base
Accuracy				Difference in static and dynamic friction
	0.2" over full range	0.1" over full range	0.05" over full range	Hysteresis, wear
Required operating space	6' x 4' x 7' - 8" high	6' x 4' x 7' - 8" high	6' x 5' x 7' - 8" high	Must fit in den or living room and be easy to get through doors
	Fit through standard door (32" x 78")	Fit through standard door (32" x 78")	Fit through standard door (32" x 78")	
Ergonomics	Easy to climb into		Force feedback controls	Human factors
	Easy to use controls	Adjustable seat height in 3DOF Fully enclosed cockpit	Fan for airflow effects Adjustable stiffness of seat	

Safety	Seatbelt	Touch sensitive grips that stop motion if user loses contact	Multiple body position sensors track acceleration and positions of different parts of body relative to base	1 lawsuit will put you out of business
	Emergency stop button	Dead-man switch	Heart rate and other monitors	
	Does not cause whiplash Use accelerometer in headgear	Compensates for persons' weight by adjusting gains (No excessive accels)	Whip-lash protection	
Actuators	Servo pneumatics	Firestone Airstrokes	Kane optimized Spirabellows	Need small translation that can be taken up by "soft" actuators
		with proportional valves	with PWM controlled valves	
Operating	Use air filters	Air filters and air dryers	Air filters and air dryers	No oil on Ma's new rug
cleanliness	Seals and wet lubricants	Dry lubricants	No lubricants	
Interfacing	Uses standard PC peripherals	Can use with some TV programs	Can use any computer	
	Uses PC as controller through special software or direct input from joystick	Define universal outputs for new industry. Outputs: position, vel, accel in all 6 DOF	Sell as entire gaming system with computer, peripherals, sound system and virtual hapatics	Need to define standar for industry to follow
Modularity/	Use 2" Bore pneumatics @ 125 psi	Up bore size for more force=2.5"	2.5" Bore or larger for lower pressure operation.	Minimize number of changes to improve performance
Evolvability		Can use same controller and work on improving control dynamics and washout filters		Make parts modular and standard for easy expansions
Manufacturing	Minimize custom made parts to reduce costs	If volumes are high enough start designing custom parts to make system cheaper and performance better	Low manufacturing cost by minimizing parts and relying on a few custom made parts. Custom made computer controller hardware	Increases volume sales = lower mfg costs

C	AIR P6NP1 Motherboard	AIR P6NP1 Motherboard	AIR P6NP1 Motherboard
O	200 MHz P6/256 KB L2 cache	2 200MHz P6/256 KB L2 cache	2 200MHz P6/256 KB L2 cache
M	64 MB Parity EDO DRAM	128 MB Parity EDO DRAM	256 MB Parity EDO DRAM
P	3.5" Floppy Drive (High-Density)	3.5" Floppy Drive (High-Density)	
U	NEC 4 disk 4X CD-ROM	NEC 4 disk 8X CD-ROM	NEC 10 disk 12X CD-ROM
T	2.5 GB Quantum Bigfoot IDE HD	9.1 GB Quantum Atlas Fast/Wide SCSI-3 HD	2 9.1 GB Quantum Atlas Fast/Wide SCSI-3 HD
E	Matrox Millenuim 4MB Graphics Card	Number 9 Imagine 128 Series 2 4MB DRAM	
R	Orchid Righteous 3D card	Orchid Righteous 3D card	
	MAG Innovsions 17" monitor	MAG Innovisions 21" monitor	Ultra high resolution HMD
S	PC Power & Cooling 250W ATX P/S	PC Power & Cooling 250W ATX P/S	
Y	Sound Blaster 32 PnP Sound Card	Sound Blaster AWE-32 PnP Sound Card	Sound Blaster AWE-32 PnP Sound Card
S	Yamaha SW60XG MIDI sound card	Yamaha SW60XG MIDI sound card	Yamaha SW60XG MIDI sound card
T	Tru-Form Keyboard	Tru-Form Keyboard	Wireless Tru-Form Keyboard
E	PC mouse	PC mouse	Wireless PC mouse
M		Dragon Dictate	Configurable cockpit button system
			Dragon Dictate
	Yamaha System 45 Sound System	Bose Acoustimass System	Bose Acoustimass System
	1 Aura Bass Shaker	2 Aura Bass Shakers (sway & heave)	2 Aura Bass shakers (sway & heave)
	CH Force Joystick	2 3D Force-feedback joystick system	2 3D Force-feedback joystick system
	CH Pro Throttle	3 pedal Force-feedback pedals	3 pedal Force-feedback pedals
	CH Foot pedals		
	CH Steering wheel		
M	MEI 3-axis motion card	MEI 4-axis motion card	Custom 8-axis motion card
O	3 6" Bimba PFC cylinders or Firestone Airstokes w/ SpaceAge control potentiometer	3 10" stroke rigid cylinders or spiralbellows	6 18" stroke sprialbellows with integral sensor
T		3 Linear potentiometers	or rigid cylinder with flex couplings
I	3 Festo proportional valves	3 Festo proportional valves	12 PWM spring spool valves
O	Silencers	Silencers	Silencers
N	Hoses, elec. connectors, and fittings	Hoses, elec. connectors, and fittings	Hoses, elec. connectors, and fittings
	125psi, 1.5hp oilless compressor with 1.75 gal tank, 4.6CFM@90psi	125psi, 1.5hp oilless compressor with 1.75 gal tank, 4.6CFM@90psi	125psi, 1.5hp oilless compressor with 1.75 gal tank, 4.6CFM@90psi
P	6 Gimbal joints	6 Gimbal joints or flex couplings	Low cost flex couplings
L	Fixed base	Rotary motion (yaw) base with sliprings	Rotary motion (yaw) base with sliprings
A	Wrap-around cockpit	Wrap-around cockpit	Wrap-around cockpit
T	Seat	Seat	G-seat with sprialbellows actuator
F	Seat cushion	Seat cushion	Seat cushion
O	4 point harness	4 point harness	4 point harness
R	Helmet with accelerometer and neck support	Helmet with accelerometer and neck support	Helmet with accelerometer and neck support
M			

4. Concept Generation

This project started as an idea to use a chair mounted to a hexapod (Stewart platform.) The monitor and controls would be on a desk in front of the user and he could sit in his seat and experience the feeling of whatever game he might be playing. This chair would be linked to a computer and the platform would move in response to commands generated by the simulation game.

After some initial research, quite a few noteworthy changes took place. The research also helped formulate new ideas and solutions to the problems at hand. Other methods were used to formulate new ideas. One of the most effective methods was simply to scan manufacturer's catalogs on both related and unrelated products. Mechanical engineering catalogs such as McMaster-Carr and Grainger provide a wide variety of different products that can be either used to form new ideas or modified in some way to provide an effective solution. *Design News, Mechanical Engineering, DesignFax,* and *Popular Science* were also looked at for new products and interesting solutions. For this project *Computer Pilot*, *Computer Gaming World, PC Magazine* and *PC Gamer* were also reviewed for the state of the market and new products. These magazines also gave some indication as to the popularity of different simulation games in comparison with strategy and arcade type games. From this data, the system should most likely only be used in seated simulations. These will include a military combat aircraft, helicopters, civilian planes, racecars, space ships, and others. Software simulation games that could be used include (but are not limited to) : Mechwarrior, IndyCar Racing, Monster Truck Madness, MS Flight Simulator, Apache, Hind, Off-Road, SimCopter, Destruction Derby, X-Wing Fighter, Descent, Privateer, Wing Commander, NASCAR Racing, Jane's ATF and AH-64D Longbow. Fortuitously, the simulation market seems to be a large share of the overall market, taking approximately 40% of the overall game sales.

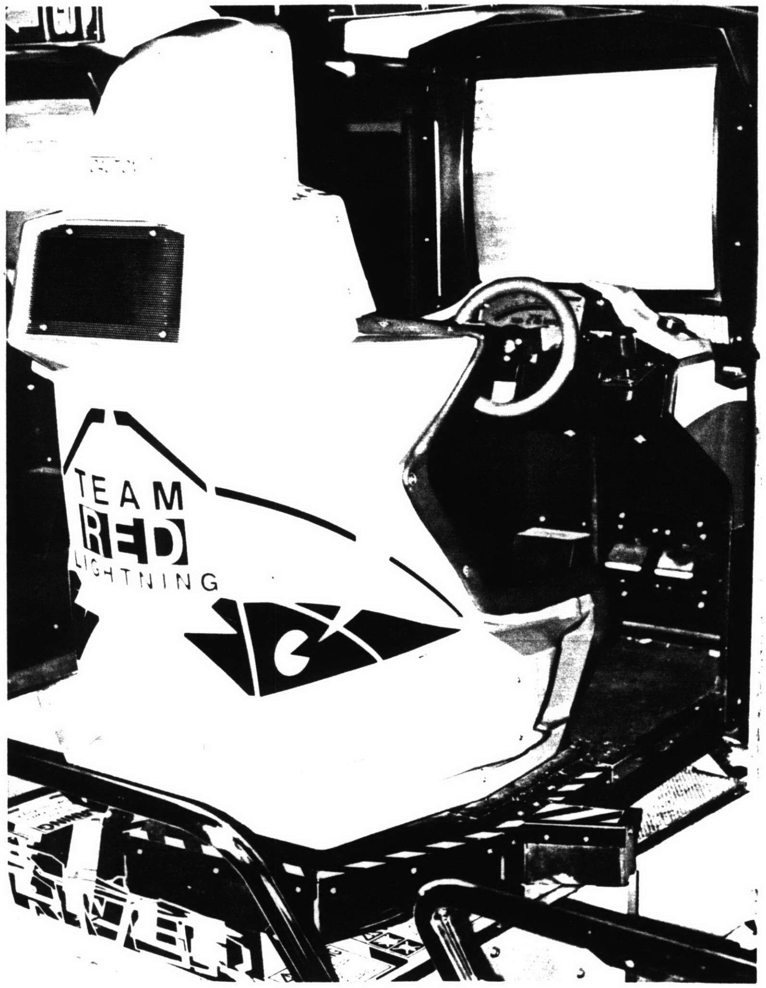
Research was also done by visiting the local arcade, noting and testing the simulation games for their realism. These games included: Desert Tank, Tokyo Wars, MANX TT Superbike, Sega Rally, Afterburner, and Ace Driver, Wave Runner; Alpine Skier and

Alpine Surfer (Figures 11 - 17), all of which were manufactured by either Namco or Sega. Much was learned from these visits. First, that the car simulators that only used yaw provided poor realism and the games that simply had force feedback joysticks and no motion were more realistic. In fact, Sega Rally with no motion and only a force feedback steering wheel was far more effective than the yaw only simulator at simulating turns. The skiing and snowboarding simulators looked interesting but were ineffective at conveying the feeling of skiing again using only yaw. A much more effective simulator would use roll and pitch and this would be far more realistic than the yaw only.

FIGURE 11 - *AFTERBURNER*, FLIGHT COMBAT SIMULATOR WITH PITCH AND ROLL

FIGURE 12 - *ALPINE SKIER*, DOWNHILL SKIING SIMULATOR WITH YAW ONLY

FIGURE 13 - *ACE DRIVER*, CAR DRIVING SIMULATOR WITH YAW ONLY



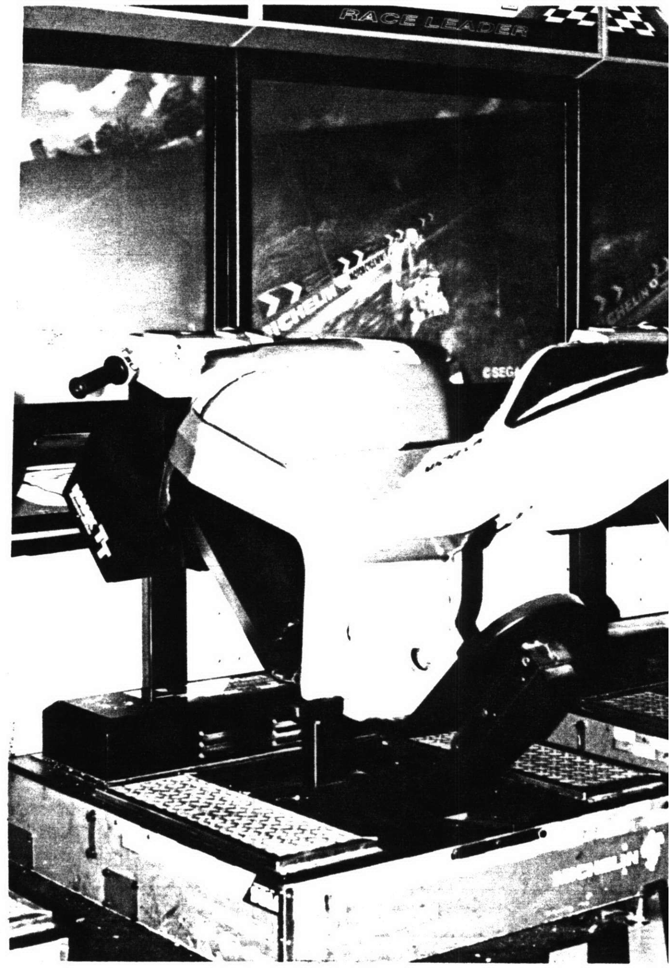


FIGURE 14 - *MANX TT SUPERBIKE*, MOTORCYCLE SIMULATOR WITH ROLL ONLY

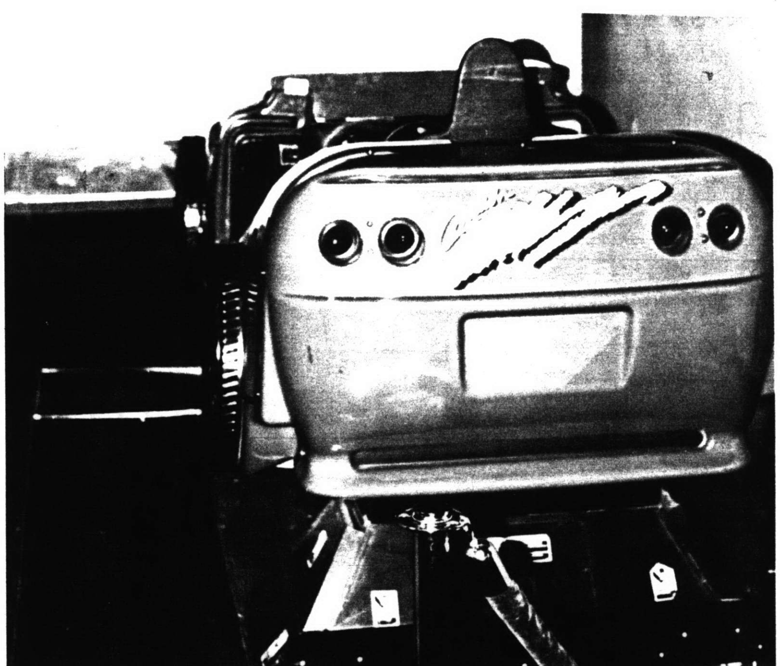


FIGURE 15 - *CRUISIN' USA*, DRIVING SIMULATOR WITH PITCH AND ROLL

FIGURE 16 - *WAVERUNNER*, JET-SKI SIMULATOR WITH ROLL ONLY

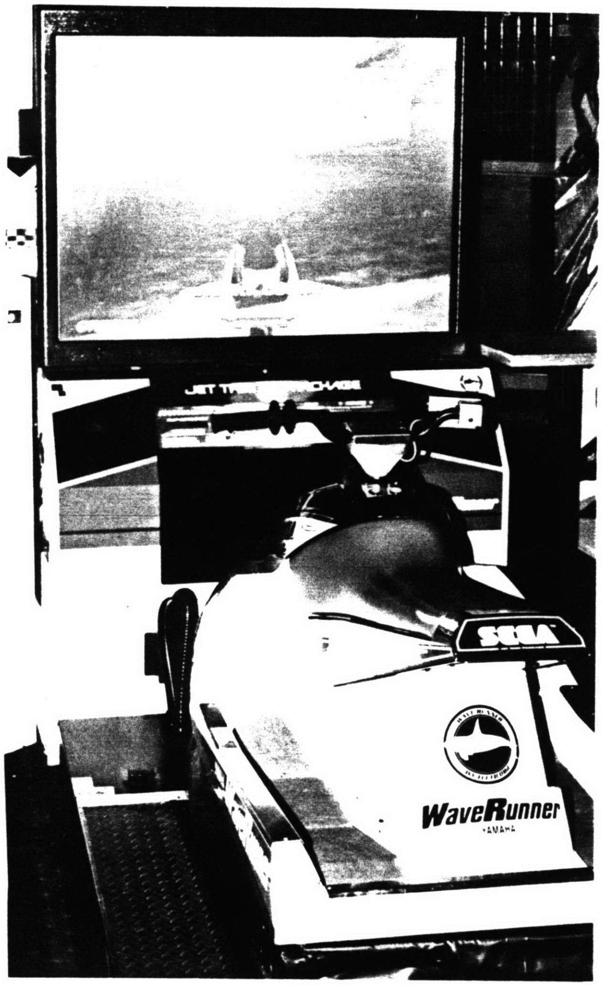


FIGURE 17 - *ALPINE SURFER*, SNOWBOARD SIMULATOR WITH YAW ONLY

AfterBurner used only pitch and roll and was rather effective but because the simulator was not totally enclosed, some degree of realism was lost. The game needs a few changes to increase its realism. First, the cockpit should be totally enclosed. Second, the addition of heave would make ascents and descents much more convincing. And finally, the pitch model used was based purely on visual orientation. This mistake was first made in 1924 by Ed Link with his *Link Aviation Trainer No. 1*. The trainer reproduced motion in roll, pitch and yaw using the visual system as a model. Unfortunately, this provides fundamentally incorrect force and motion cues[4]. The pivot was located below the cockpit, some distance from where the aircraft CG would be, and

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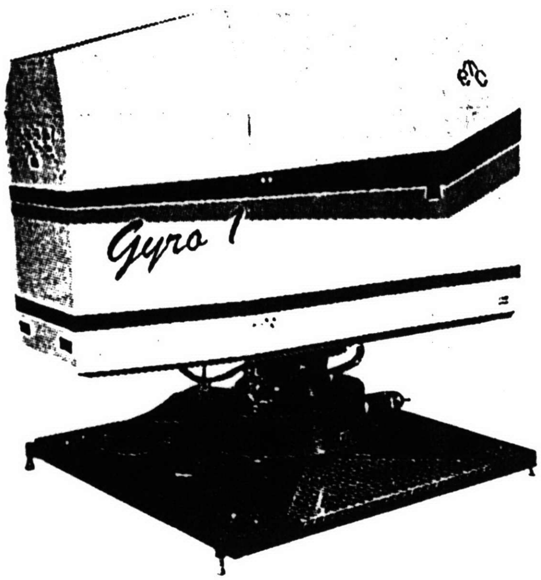
[4] Brown, Y.J., et. al. "Need Based Evaluation of Simulator Force and Motion Cueing Devices."

made rolls feel more like slip motions. The motions of the simulator need to be based on the vestibular, tactile and proprioceptive sensors. For this reason, the user must be placed in a light tight box, so that the visual system does not have any reference points outside of the simulator.

The motorcycle-racing simulator used a full size motorcycle and allowed the user to control the roll. However, there was no force feedback in the roll and it would have benefited greatly from this. The addition of small motions in pitch and heave would have added greatly to the simulation. For the motorcycle simulation, a small amount of yaw would have also effectively added to the realism of turning and side slipping.

By researching military and commercial flight simulators and also requesting information from various commercial companies, a wide variety of concepts were found (Figure 18 and Appendix A). Furthermore, a rough idea of the lateral and rotational accelerations that were required was gained from high-end commercial flight simulators.



Motion Base

Range of motion
± 15° Pitch
± 30° Roll
± 360° Continuous Yaw

Angular velocity
0-10° per second Pitch
0-10° per second Roll
0-15 RPM Yaw

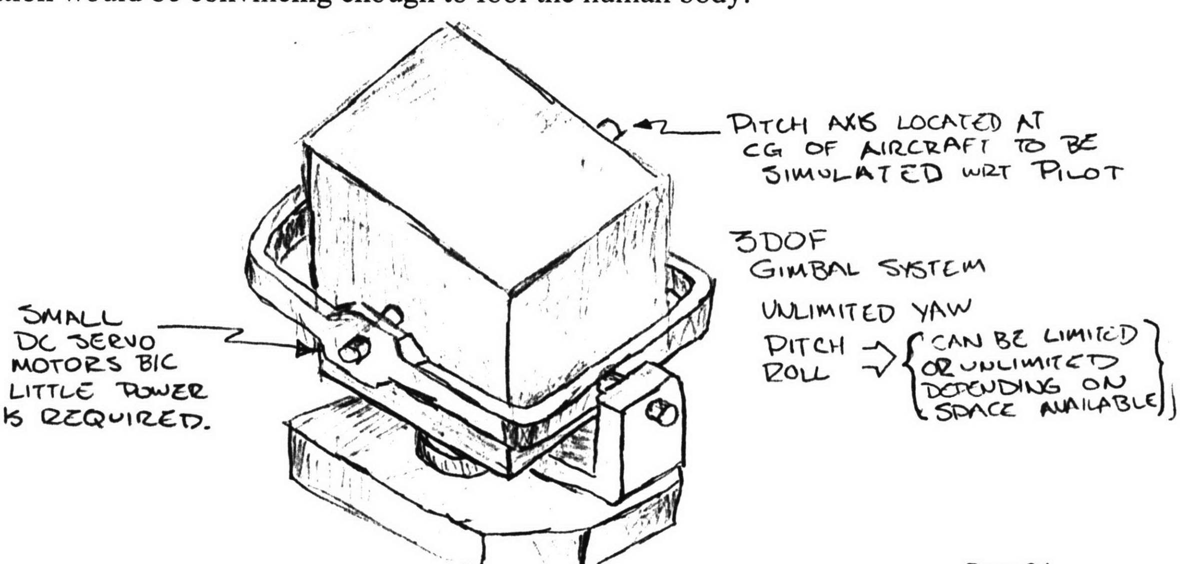
Angular acceleration
0-25° per second^2 Pitch
0-25° per second^2 Pitch
0-10° per second^2 Yaw

FIGURE 18 - A THREE-DEGREE OF FREEDOM SIMULATOR UTILIZING PITCH, ROLL AND YAW

This data was a good reference and was the basis for most of the concepts. The first concept was a hexapod configuration, capable of 6 DOF, in which a fully enclosed cockpit was mounted to the upper platform. One limitation of the Stewart platform is its limited yaw capacity. Thus, the first concept was modified to mount the lower platform of hexapod on a rotary table. This would allow a full 360° of rotation as compared with perhaps 20° or 30° of rotation possible with the hexapod.

Both these systems seemed expensive, so an alternative idea was to use only three degrees of freedom, which would also simplify control. Since surge can be simulated by pitching and sway can be simulated by rolling, roll and pitch were ideal motions to reproduce since they would effectively give four degrees of freedom. The other two motions, heave and yaw were not yet simulated. Thus, one concept was to use three vertically mounted pistons, which would provide pitch, roll and heave (vertical translation). This system could not reproduce yaw, so the next concept used the 3 DOF platform mounted on a large rotary table, which would provide 360° of continuous yaw motion. This 4 DOF platform could not truly reproduce sway and heave, so the next concept attempted to fix this by providing a limited motion in both of these directions.

To reproduce sway and heave, a flexure and voice coil system could be used to produce a very limited motion (2" to 3" of translation) with minimal expense. The flexure and voice coil system was a bit complex and bulky, so other options were explored. A G-seat could reproduce the heave motion by using the increasing pressure on the back. Used in combination with visual cues and the false gravity cue achieved by slightly pitching the platform, this could be an effective simulation of short and sustained accelerations. Unfortunately, sway motion was still not accounted for. To achieve sway, perhaps a 2 DOF G-seat could be made. By increasing the pressure on one side of a person's buttocks, rolling slightly and visually simulating a sway motion, this combination would be convincing enough to fool the human body.



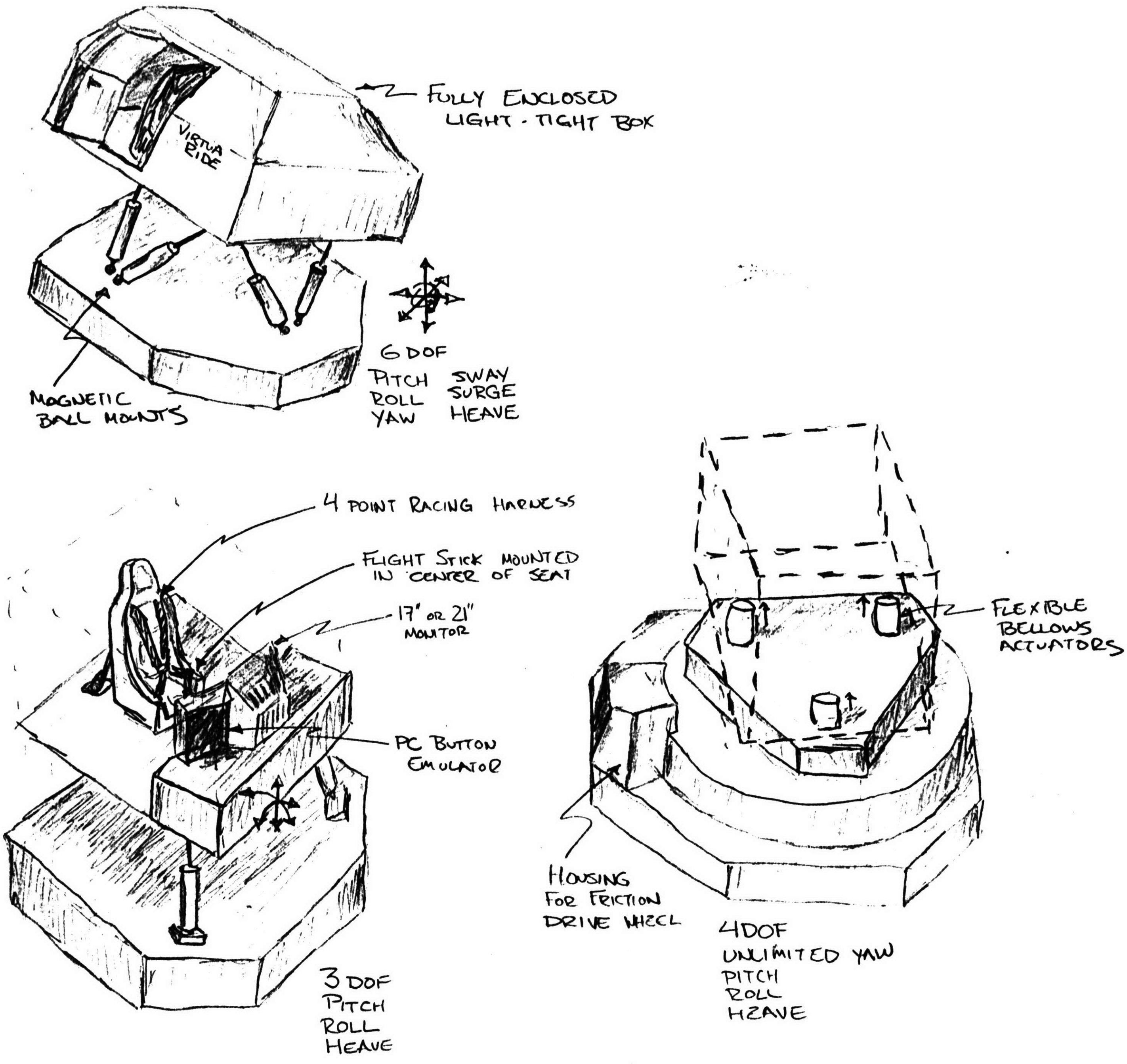


FIGURE 19 – CONCEPT SKETCHES OF SOME OF THE PROPOSED IDEAS

Starting a new line of thought, perhaps a yaw, pitch and roll system could be used with the translation motions simulated in another manner. One elegant system would be to make the cockpit in a fully enclosed sphere and then driving the sphere continuously in all rotation axes. In this way, roll, pitch and yaw are not limited at all. A loop performed in a fighter plane could be simulated without any washout as would be necessary with a hexapod or the 3 and 4 DOF system developed earlier. As mentioned earlier, surge and sway can be simulated with motions in pitch and roll but heave cannot be simulated by any combination of these. However, a single large actuator could be used to power a heave motion, but it must be quite strong as it must fight gravity to lift the user, the cockpit and the motors that drive the three rotation axes. The complexity of ball drive motors or making friction wheels that slipped orthogonal to their drive motion seemed rather complex and expensive. Also, some type of RF communication would need to be used to communicate to anything in the sphere. Thus all inputs (keyboard, joystick, foot pedals, etc.) and outputs (force feedback, and visual display) would need to be wireless. Cheap IR communication could not be used as the outside of the sphere is opaque and the drive surface for the motors. In addition, a battery or some type of induction would be needed to drive the monitor and other peripherals inside the sphere. This system has many benefits but initially seems somewhat complex. Thus, a gimbal system that would limit pitch and roll and yaw was investigated. With this system, slip rings could be used and the problems of power and communication through the sphere are alleviated. This system would be lower cost and could add a heave motion if deemed necessary. Furthermore, each axis could be driven by a low cost friction drive without having to worry about slipping orthogonal to the drive direction

While generating concepts it is also useful to be thinking about what the ideal simulator would be like. What improvements might be possible in 2 years, in 5 years and in 10 years. If the designer is thinking about future improvements, the design can be designed with these future improvements in mind. Such a system will be successful in the future because it will be able to be upgraded and keep up with new technology. Table 2 contains a theoretically ideal system at the present time, in the near future, and in the far future.

5. Concept selection

All of the concepts generated in the previous step were laid out and a Pugh Chart was made to look at the strengths and weaknesses of each concept. A Pugh chart is a table that lists all the design concepts on one axis and the desired characteristics on the other axis. A standard or datum is chosen and all other designs are compared to it as either better, worse, much better or much worse. The results are tabulated but , should not be used as a final decision-maker. The Pugh chart is much more effective as a tool to realize the strengths and weaknesses of each design. The hexapod offered the most realistic motions with the exception of yaw, although by adding a rotary table to the hexapod, it would clearly be the most versatile motion simulator. However, in terms of cost and controller complexity the hexapod lost to the simpler concepts. One benefit of the 3 DOF platform was it could be easily upgraded to the 4 DOF by adding a rotary table. It could be further upgraded to a 5 DOF or 6 DOF by adding a 1 DOF or 2 DOF G-seat. Another interesting feature of a 3 DOF motion platform is the fact that two other degrees of freedom (surge and sway) can be simulated without adding any more actuators. By pitching the seat back slightly, a short sudden acceleration or a sustained acceleration can be created. Similarly, decelerations and side accelerations can be simulated by tilting in pitch and roll, respectively. The Pugh chart is created to promote mixing good designs into designs that capitalize on the strengths of each design and use them in combination to create a few more superior designs. Regardless of whether or not this combination of ideas is possible, a more informed decision can be made with the Pugh chart data. The Pugh chart (Table 3) is shown on the next page.

Final Pugh Chart

	Stewart platform (6DOF)	Stewart platform with 360° rotary base	3 DOF platform with rotary base (4 DOF)	3 DOF platform	3 DOF platform on ball driven cart (6 DOF)
Cost		-	+	++	0
Manufacturability	D	-	+	+	-
Reproduction of motions	A	+	-	-	+
Difficulty of design		0	+	+	-
Required size	T	0	+	+	-
Weight		-	+	+	-
Ergonomics	U	0	0	0	0
Safety		0	0	0	-
Evolvability	M	0	0	0	0
Modularity		0	+	+	+
Total	0	-2	+5	+6	-3

(Note: This is only a partial list of the Pugh chart. Many concepts were developed, rated, improved upon and developed further. This chart only compares some of the most promising designs.)

The Pugh chart is just one tool that can be used to assist the concept selection process. Other more quantitative methods have been developed to help assist engineers. The QFD chart or House of Quality developed by Don Clausing is a more quantitative method and more information can be found by reading *Product Design and Development*. Another method called the Analytical Hierarchy Process (AHP) is a useful tool, especially for large projects with many engineers. Once setup, the AHP helps engineers focus on the most important goals. Other tools exist to help the engineer quantify the selection process, but each engineer must find their own method which they prefer and this process can be some combination of these or other methods as well as some process of your own. Whatever method is used, the engineer should at the very least take the time to look at each concept that was generated and evaluate its strengths and weaknesses.

6. Patent Search

As this product is to be eventually marketed to the public, an investigation into the existing patents was needed to ensure no patents were infringed. Perhaps some insight might be gained as to other possible solutions. The patent search can be done at any time during the design process, but the later in the process it happens the more work might be lost if the device being designed has already been patented. Therefore, an expeditious yet broad patent search is recommended early on. One might consider this search part of background research. Most of these patents were retrieved in full at http:\\patent.womplex.ibm.com, but only the first page is shown in Appendix B.

Patent #4,019,261 describes a system that uses three degrees of freedom: pitch, roll and heave. The motion system is cascaded and unlike the three DOF platform proposed in concept generation. The heave axis is totally separate and thus requires 3 times the actuator force than the proposed system. One actuator is responsible for lifting the entire mechanism. While it might be argued that gimbaling the system about the CG allows pitch and roll actuators to be small, the heave axis must be powered by a very large actuator and supported by large and expensive linear bearings.

Patent #4,066,256 uses three hydraulic actuators mounted vertically upward in much the same way as the proposed system. However, hydraulic cylinders are used and the motion platform is for roughly 20 passengers at an amusement park.

Patent #4,551,101 again uses just 3 cylinders for motion in pitch, roll and heave, but uses a interesting set of scissors as a means of bearing support and constraint. This allows pitching about an axis running through attachment points 4 on posts 1 and 2 (see Appendix B) and roll about the axis perpendicular to post 3 running through attachment point 4.

Other relevant patents include, but are not limited to, #4,576,577, #5,453,011, #4,887,967, #5,509,631 and #5,366,375.

7. Pneumatic Systems Research

The choice to go with a limited 3 DOF base was a hard one. Although complexity and high cost ruled out a hexapod configuration, there were still many other options and design variables. To address these different design issues, spreadsheets were written to help optimize these variables. One was written to address the optimal placement of the actuators, their bore diameters, stroke lengths and operating pressure. This spreadsheet (Table 4) is shown on the next page with the optimal values for Bimba cylinders.

Another test was setup to determine the feasibility of using pneumatic actuators. Servo control of pneumatic cylinders is a relatively new field and many questions needed to be answered. Pneumatics are by their nature compressible and therefore inherently unstable. To control these systems, all components have to operate at high frequencies: valve, A/D converter (for feedback), and the control loop must be updated quickly.

VirtuaRide Project   Prepared by Keith Breinlinger 8/30/97

Sizing & Placement of 3 actuators

Change only colors in blue!!!

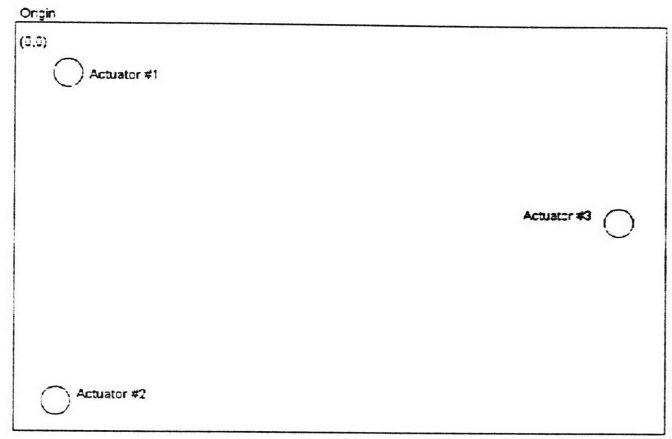
Max force for each actuator

	Pressure (psi)	Diameter (inches)	Force (lbs)	Force (N)	Stroke length inches
Actuator #1	**110**	**2**	345.58	1537.19	**18**
Actuator #2	110	**2**	345.58	1537.19	18
Actuator #3	110	**2.5**	431.97	1921.49	18

Distance between Actuator 1 & 2 (y distance)	**35**
Distance between Actuator 1,2 & 3 (x distance)	**59**

POSITIONS	x	y
Actuator #1	0.5	0.5
Actuator #2	0.5	35.5
Actuator #3	59.5	17.75
CG of platform	23	18

Platform limits	
0	0
60	36
500 *lbs at CG*	



Max excursions	**VR chair**	**GAT-II trainer**
	inches or degrees	
Vertical	**18**	**0**
Roll	**27.22**	**30**
Pitch	**16.97**	**15**

User weight	200 *lbs*
I roll	32000
I pitch	94100

Max forces			**Acceleration**		
	lbs or in-lbs		**VR chair**	**GAT-II trainer**	
Vertical	1123.12		**1.25**	**0**	*G's upward*
Roll	12203.12	*Torque about CG*	**21.85**	**25**	*deg/sec^2*
Pitch	17494.74	*Torque about CG*	**10.65**	**25**	*deg/sec^2*

Needed translations

			Translation in inches	
For roll motion	0.475010355	Actuator #1 & #2	2.178665	along y axis
For pitch motion	0.296114896	Actuator #3	2.684677	along x axis

The first step was to determine the necessary stroke, bore and operating pressure needed to drive the system. The valve C_v and maximum operating frequency needed to be determined. Finally, the compressor and reservoir tank (if any) needed to be sized. The bore and stroke were determined with an Excel spreadsheet (shown on following page) to optimize placement of the actuators, bore size, stroke length, and operating pressure. A general aviation trainer (GAT-II, Appendix A) produced by Environmental Tectonics Corp. was used as a baseline for pitch and roll capabilities. The bore and operating pressure was constrained by the general rule to exceed the force capabilities by a minimum of 33% of the maximum load and the compressor pressure should be 20% greater than the maximum required design pressure[5].

The C_v value is analogous to electrical conductance. To determine the maximum operating frequency the cylinder can be driven at, the smallest orifice in the system needs to be determined. That orifice will have the lowest C_v value of any other component in the system. If this component is approximately the same C_v as most of the other components in the system, the system has been well laid out. If, however, the C_v value is much lower than all other components, the system could be greatly enhanced by simply changing the limiting orifice. The governing equation for flow rate through a fixed orifice (from Bernoulli's theorem) is:

$$\mathbf{Q = 22.48\, C_v\, [(\Delta p p_{2a})/(\Gamma_{1a} G)]^{1/2}} \qquad \text{(Eqn. 1)}$$

C_v ⇒ flow coefficient of a fixed orifice pneumatic device

Γ_{1a} ⇒ temperature in absolute terms using degrees Rankine (°R) (°R = °F +460)

p_{1a} ⇒ initial upstream pressure in psia (psia = psig + 14.7 at sea level)

p_{2a} ⇒ final downstream pressure in psia

Δp ⇒ pressure drop in psi ($\Delta p = p_{1a} - p_{2a}$)

G ⇒ specific gravity of air (= 1 for air @ 14.7 psia, 68°F, 36% rel. humidity)

If $p_{2a}/p_{1a} \geq 0.533$ the flow is critical. So assuming this, (for maximum operating frequency) Eqn. 1 can be simplified to:

$$\mathbf{Q = 0.489\, C_v\, p_{1a}} \qquad \text{(Eqn. 2)}$$

[5] Fleischer, Henry. *Manual of Pneumatic Systems Optimization*

For our system we use ¼-NPT fittings. The smallest diameter is 0.313 inches and thus this becomes the controlling orifice. For the orifice the C_v is approximately 23 times the diameter squared. (See Appendix C for discharge coefficients of various orifice shapes.)

$$C_v = 23d^2 \quad \text{(Eqn. 3)}$$

Thus our Cv becomes 2.25 and inserting this into Eqn. 2 with an initial pressure of 75 psig, the volumetric flow rate becomes 98.69 scfm. The fill volume equals:

$$V = \pi/4\,[(B^2S) + (d_t^2 l)] \quad \text{(Eqn. 4)}$$

- B $\Rightarrow$ Bore of cylinder (in inches)
- S $\Rightarrow$ Stroke length of cylinder (in inches)
- d_t $\Rightarrow$ diameter of tubing after limiting orifice (in inches)
- l $\Rightarrow$ length of tubing after limiting orifice (in inches)

Thus, for our 1.5" bore, 18" stroke Bimba cylinder with 5/16" tubing and a length of 12 inches of tubing from the valve to the inlet port of the cylinder, the fill volume is 32.73 cubic inches or 0.0189 cubic feet. To pressurize this volume to a pressure of 33 psig, which would effectively move a load of 38 lbf, requires 0.0613 scf. Therefore, our cylinder could extend vertically upward, lifting a 38 lb. weight in 0.037 seconds with a supply pressure of 75 psig. This is a good first order approximation but the inertia of the load was not considered and also the pressure difference between the supply pressure and cylinder pressure changes dynamically as the cylinder extends. In a study by Henry Fleischer, he measures the changes in pressure of a double-acting cylinder with a supply pressure of 80 psig. The figures below show both extend and retract times and it can be seen that a significant pressure builds up in the exhaust chamber as the cylinder rushes forward. It is also interesting to note that the cylinder pressure does not build up to the supply pressure until well after the cylinder has reached the end of its stroke.

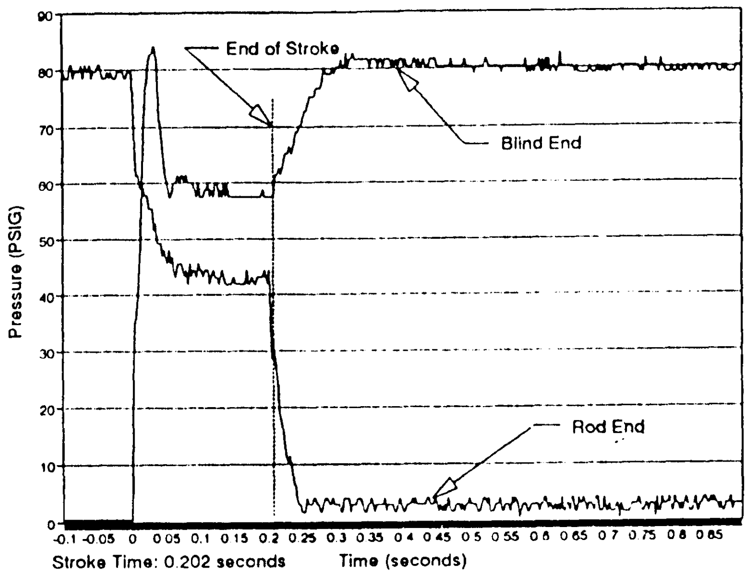


FIGURE 20 – TWO INCH BORE, 6 INCH STROKE CYLINDER EXTENDING (80 PSIG SUPPLY)

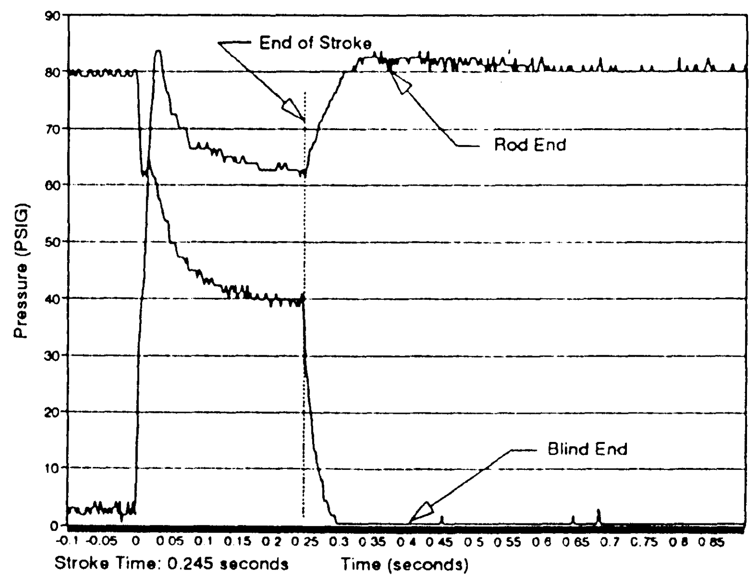


FIGURE 21 – TWO INCH BORE, 6 INCH STROKE CYLINDER RETRACTING (80 PSIG SUPPLY)

From this work, a few of design axioms may be developed toward a more effective and efficient pneumatic system. The C_v values of all system components should be considered and all should allow similar flow rates. One might argue that only the smallest is important and all others are negligible to the system. This is true, except if one was to purchase all of these components, each larger component will likely cost more than a smaller one so it is important to know all the system C_v values. It is also important to minimize the length of the conductor to the inlet port of the piston as this causes a delay and longer stroke times. Finally, it is noted that for systems that are moving forces against gravity, a large pressure is needed to overcome this. However, when the system retracts and gravity is now assisting the motion the large pressure is not required. If a dual-pressure system was used, the exhaust pressure build up as seen in Figure 20 would be reduced thus increasing extend speeds while maintaining retract speeds. This system also requires less air and thus a smaller compressor may be used.

8. Feasibility Study

A test bed was constructed using a 1.5" bore and 18" stroke Bimba pneumatic cylinder (Figure 22 and Appendix D). A Festo high-speed 5 port, 3 way valve (Appendix E) was used and the feedback was a linear potentiometer built into the Bimba cylinder. The control system used was made by MEI (Motion Engineering, Inc.) and the system used a 12-bit A/D conversion for the potentiometer (Appendix H). A PD (Proportional-Derivative) system was implemented in the following test so some steady state error did occur. However, the addition of an integral term led to instability caused by the stick-slip problem, which will be discussed in greater detail later. The stick-slip problem was avoided by using a Firestone flexible actuator and was also tested using the same testing apparatus (Figure 23.)

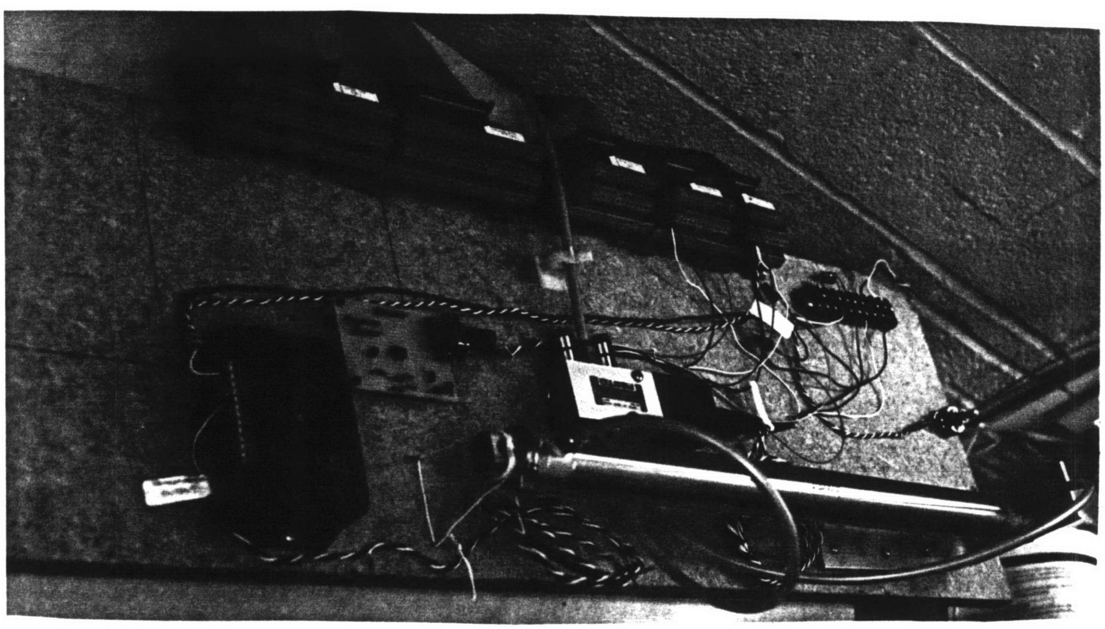


FIGURE 22 – 1.5" BORE, 18" STROKE BIMBA CYLINDER ON TEST BENCH

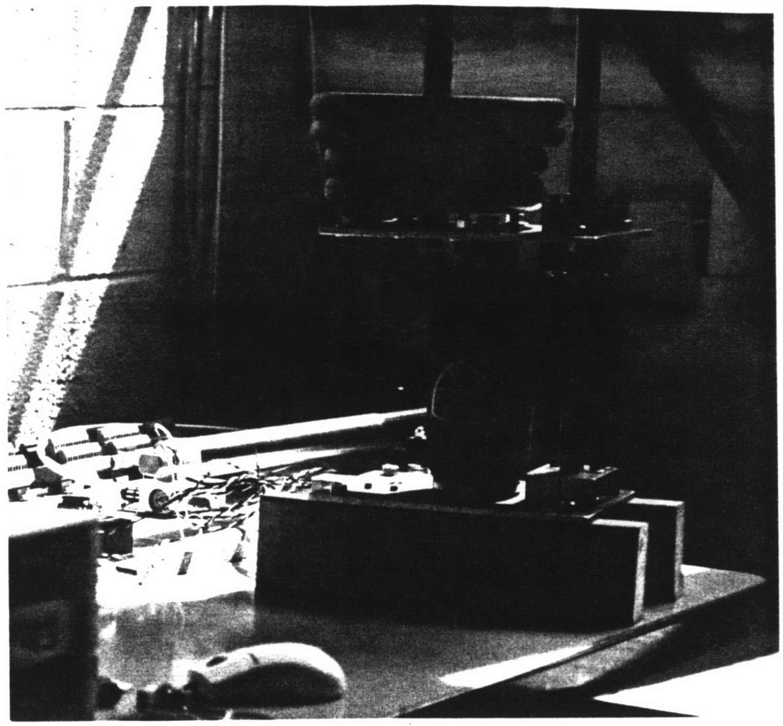


FIGURE 23 – FIRESTONE AIRSTROKE ACTUATOR ON TEST BENCH LOADED WITH 45 LBS.

Bimba Cylinder Data (for 18" Bimba cylinder with PD control)

- ±0.04" positional accuracy (limited by poor response of linear potentiometer
- 13 in/s^2 (limited by instability of controller with no load or damping)

A data acquisition program was written to record the commanded position, the actual position (as determined by the A/D converter and therefore limited in resolution) and the command voltage to the valve. (The C program code is listed in Appendix F.) This data was taken at various pressures, loads and PD filter parameters.

8. Embodiment

There needs to be at least two prototypes made before a low scale production can begin. The alpha prototype should be an easily configurable test bed such that different equipment may be easily interchanged and tested. Many parts for the alpha prototype will be more expensive than the production version. However, these parts should allow adjustments to be made so that the optimal configuration can be found. The alpha prototype's major function is to test the equipment in various configurations and optimize the ergonomics, dimensions, weight distribution and other factors.

The alpha prototype that was constructed is a nearly complete system, including the computer, software, input devices (joysticks, pedals, and throttle controls), a 3D sound system and, of course, the motion platform. Mounted on the platform is an adjustable chair (for ergonomic tests) with a safety harness, the monitor, and bases for the input devices.

The platform is connected to the base by three pneumatic cylinders, which provide motion in pitch, roll and heave. The motion platform was originally designed to be driven by pneumatic cylinders, but this would require a complicated system of gimbals and/or linear slides to account for the cosine motion when pitching or rolling the upper platform. A simpler system was devised to use flexures and pin hinges, but even that was improved on by switching from pneumatic cylinders to flexible bellows-type actuators. These actuators are manufactured by Firestone (Appendix G) and consist of a rubber material bonded on top and bottom to a metal plate. By fixing one side to ground and the opposite side to the upper platform, motion is achieved by inflating the bellows. Due to the flexible nature of the rubber bellows, no flexures or pivots are needed when pitching or rolling the platform. Control of the height of each bellows is achieved in the prototype version by using the 5 port, 3-way valve that was used for the double-acting Bimba cylinder. This is not the ideal valve since the control of a single acting cylinder (such as the bellows) requires only a 3 port, 3-way valve whereas the double acting cylinder requires 5 ports. As cost is the most important factor in this design, a few other alternatives are discussed later to lower the cost of these valves.

The use of flexible bellows actuators solves two problems. As discussed above, it eliminates the need for gimbals or pivot mounts and flexures or linear slides. It also solves a common problem that exists with all pneumatic cylinders which is called stick-slip. The stick-slip problem occurs in pneumatics when attempting to move a small distance. More air is added to one side, pressure builds up, and this increase in pressure must overcome the static friction at the seals. Once this is overcome, and the piston begins to move, the friction at the seals drops dramatically. This somewhat sudden change causes the piston to burst forward and overshoot the desired position. This problem makes precise position control difficult. However, if great precision is not needed, then a servo pneumatic system may be an excellent choice. The double-acting Bimba cylinder was able to easily achieve a position to within 1/10". With some filtering and more advanced control, position control to within 1/100" is feasible. Adding a hydraulic damper[6] would decrease the stick-slip problem by increasing the total system friction. When the friction at the seals transitions between static friction and dynamic friction, the drop in friction can be ten percent (or less) of the starting friction. The damper reduces this change in friction such that this change is only half (or more) the starting friction. The damper has its disadvantages: it increases friction, requires more power and makes higher speeds difficult. Luckily, the Firestone bellows have no seals and thus there is no stick-slip problem. There is a small spring force inherent in the rubber bellows but it is negligible and does not affect the controller design. Finally, the cost for each of the bellows is rather inexpensive at roughly $50 per piece. They do limit the maximum extension of the platform and thus each bellows can extend only about eight inches as opposed to 18" or more that is possible with a hard walled cylinder.

The position sensors for the Bimba cylinders are built into the cylinder and the fixed body provides an easy place to mount a linear potentiometer. For the flexible bellows a linear potentiometer would not be so easy to mount. A variety of different options existed, and the same process that was carried out in the design of the overall system was used again for the design of the position sensors. One idea was to make gimbals mounts or magnetic ballmounts and attach a rigid potentiometer or LVDT. A LVDT turned out to be more accurate and expensive than was necessary so the idea of using a potentiometer due to its low cost seemed a good solution. Also, if a damper was used the damper and linear potentiometer could be combined. After some more research another interesting product was found which was manufactured by SpaceAge Controls. Their system mated a cable reel to a rotary potentiometer or an encoder. This system does not require any gimbals or ball mounts as the cable is allowed to exit the reel anywhere in an approximately 30° cone. This range more than allows for the maximum flexibility of the motion platform. It also allows the cable to be mounted closer to the edge of the bellows than would be possible with a linear potentiometer.

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[6] Dawson, David. *Advances in Actuators: Fluid Power Actuators*

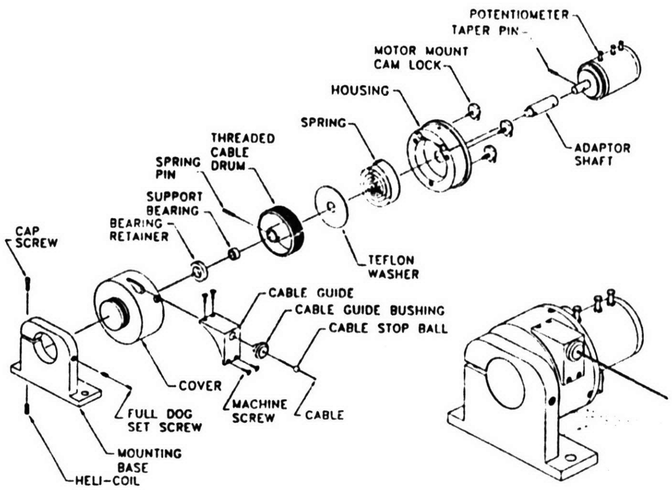

FIGURE 24 – THE SPACEAGE CONTROLS LINEAR POSITION SENSOR

The sensor is ideal for this application and it uses a conductive plastic potentiometer rather than a wound wire one thus providing a smoother and more accurate reading. These potentiometers also last longer than their most of their wire wound counterparts. The potentiometers are used as voltage dividers rather than as rheostats because the former system tends to be more accurate. A conductive plastic linear potentiometer is favored over the wire wound type because the plastic is much more linear and not prone to skipping. Unfortunately, the SpaceAge system (which utilizes the conductive plastic potentiometer) costs nearly $500 per sensor. However, the parts to make such a system would cost only about $30 and even for low-scale production of 100 pieces, which would produce only 33 motion platforms these pieces could be made for less than $60 per piece.

The most expensive part of the system is the valves and thus is the area that should be investigated to reduce overall costs. Each 5 port, 3-way valve costs $500 while a typical 3 port, 2 way valve can cost as low as $40. If one or even two of these can be used per axis this would result in a savings of $400 per axis, thus a total system savings of $1200. This cost is the manufacturing cost and thus the savings to the consumer could be $2000 or more. To use a standard valve costing $40 a PWM control logic that is built into the FESTO valve would need to be designed a manufactured. If the valve spool has a high enough operating frequency, the system would be able to control the Firestone bellows actuator. Typical spool valves have a maximum operating frequency of 20-50 Hz and since the actuator is only expected to operate at a max. frequency of 1-2 Hz, these valves should be sufficiently fast to control them. The proposed system would use one on/off valve that would have no proportional control capability. That valve would be supplied by an on-off valve that is being controlled with a PWM driver. This setup would in effect be a 3-way, 3 port valve, but it would be constructed from one 2-way, 3 port valve and a 2 way, 2 port valve. This system is one of a few different types of valve systems that is proposed for future cost reduction. Another system would use two valves each PWM controlled and mounted directly to the input and exhaust ports. This system would minimize the conductor flow length and make dynamic braking possible. This system could be used for both rigid (air cylinder) and flexible (bellows-type) actuators[7] and could utilize a dual-pressure scheme as discussed in section 7.

Another possible system would use a bank of valves with exponentially increasing volumetric flow capacities. If the smallest valve was 0.01 in^3/min, the next valve would be 0.02 in^3/min, followed by 0.04, 0.08, 0.16, 0.32, 0.64, 1.28, 2.56, and 5.12 in^3/min. Therefore by simple on off control, this system with only ten on-off valves could achieve any flow rate from 0.01 in^3/min to 10.23 in^3/min in increments of 0.01 in^3/min. If manufactured in large quantities, this system might be very economical and could be driven by an incredibly simple control system as the fluid system is really a binary counter of sorts. No digital to analog converter would be necessary, the control would be truly digital. Furthermore, the smallest valve will need to have the highest operating frequency, while the largest valve will most likely be driven at the slowest frequency. This is ideal because the largest valve will have a much larger mechanical inertia and will be unable to operate at very high frequencies.

The controller board used to do the A/D conversion and calculate the PD control loop is manufactured by Motion Engineering, Inc. Their control system outputs a voltage using a 16-bit D/A converter. The output frequency for the control voltage is roughly 2 kHz. The MEI 4-axis PC-DSP card we purchased for $3000 with all accessories has the

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[7] Sira-Ramirez, Hebertt and Orestes Llanes-Santiago. *Dynamical Pulse-Width-Modulation Control of Rigid and flexible Manipulators*

following specifications. In quantities exceeding 100, we can purchase the card for $500 or less.

MEI PC-DSP 4 axis motion control card

Digital Sampling Rate	4 kHz (maximum)
Servo Output	± 10 V DC @ 16 bit resolution
Input Position Feedback	5 MHz (maximum)

Due to the nature of the prototype, screw terminal connection blocks were purchased to make reconfiguration easier. In the production version, a special cable would be made such that only one cable would exit from the computer and it would be plugged into the base of the motion platform. The only other connection needed would be for a 110V AC power plug to be connected to the base. This power would drive a small air compressor and a 12V DC power supply (the computer power supply would not provide enough power).

The beta prototype should look, feel, and in every detail be exactly like the production version. The only difference between the beta and the production models should be the method of manufacture. This distinction is permitted considering that many of the manufacturing methods for production are uneconomical unless thousands or even millions are made. So if a part is to be injection molded in production, it could be machined in the beta version as long as the plastic material was exactly the same.

9. System Layout

The system takes user inputs from standard PC peripherals such as joysticks, car driving wheels, flight control pedals, the keyboard and other devices and relays these commands to the computer running the software game. The software game must then output to the monitor and also to the motion control platform. It would do this through the MEI card that must be installed in the computer.

There are two basic modes that the motion platform would be used are a driving simulator and a flight simulator. In the driving mode, a steering wheel, 3 pedals (clutch, brake and gas) and a 6 position shifter would be used. In the flight simulation mode, a joystick mounted in front of the seat, a throttle control on one side and two pedals are used. Attached to the seat on both sides is a small platform where input devices can be used by both right and left handed users. An adjustable platform is provided for either a steering wheel or a flight stick and this platform can be positioned directly in front of the user at various heights. An adjustable foot bed is also provided for the pedals for a car, plane or helicopter. At the present time, Thrustmaster makes the most popular of these input devices, but they lack much of the realism that customers demand. Other companies including Microsoft and CH Controls and other companies are starting to make force feedback devices and there should be some large changes in this market very soon.. Fortunately, the system does not rely on any special type of input device and they can be upgraded without any changes to the motion system as the market moves forward. Another side project beyond the scope of this thesis would be to look at the current technology of input devices and design a new and improved system for the home users

At present the largest high resolution monitors (1280 X 1024) that can be used have a viewing area of approximately 20" across the diagonal in a 4:3 ratio. This is not very realistic when we consider that driving in a car, or flying in a plane, the user would typically have a front viewing area of 24" x 60" or more. Furthermore, there are usually side windows that are 24" x 30" or more. To solve this problem in high-end simulators, a few different approaches are taken. One approach is to use multiple monitors so three monitors might be implemented as the front window and two more monitors, one on each side, used as side windows. Home PCs do not have the capability to do drive more than one monitor and thus we could not use this approach at this time. Also each 20" monitor costs roughly $1500 and 17" monitors cost $800. Other simulators use wrap around screens with special projectors. Again this could not be implemented in the home at this time. Another option that is commercially available and can be driven with home PCs, is virtual reality glasses. These are ideal in the fact that the software can program in any size window and any number of windows including rear windows and even sunroofs.

However, at this time the resolution is greatly limited and these are not the ideal solution. At this time a 20" monitor located in front of the user and no other monitors is the most cost effective solution. One very effective solution is to use a Fresnel lens just in front of the monitor; this creates a larger image and also focuses the image at infinity. This makes for a much more realistic viewing. Another option that can be used is to divide the image of a single monitor into two screens: the aircraft panel and the window by using a series of mirrors.

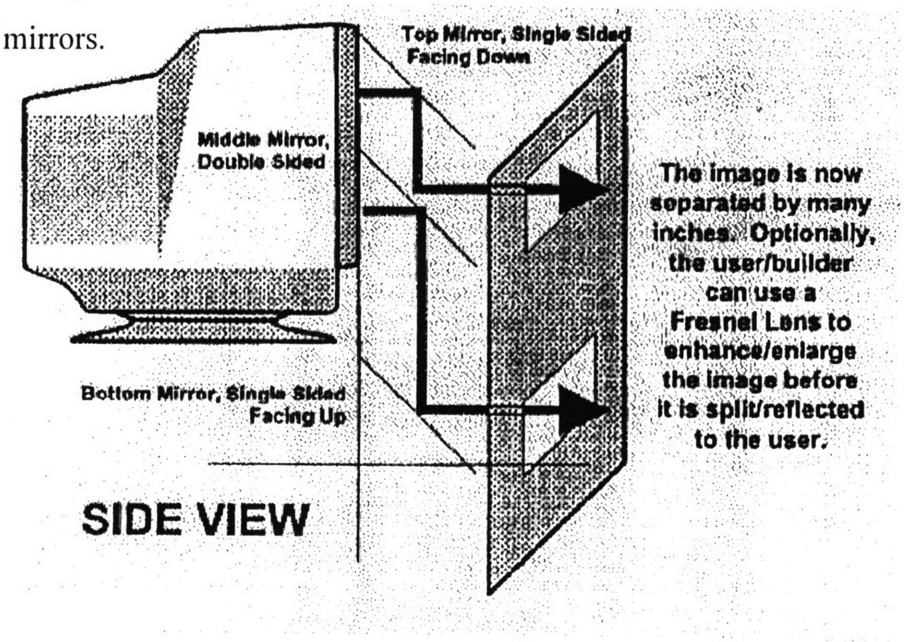


FIGURE 25 – USING A SINGLE MONITOR AND MIRRORS TO CREATE A MORE REALISTIC COCKPIT

Users could customize the interior of their simulator with different monitors such as a 27" or 32" monitors, but at the present time these are limited to 640 x 480 resolutions. Again, since the monitor does not influence the motion platform, this can be changed as the viewing technology does.

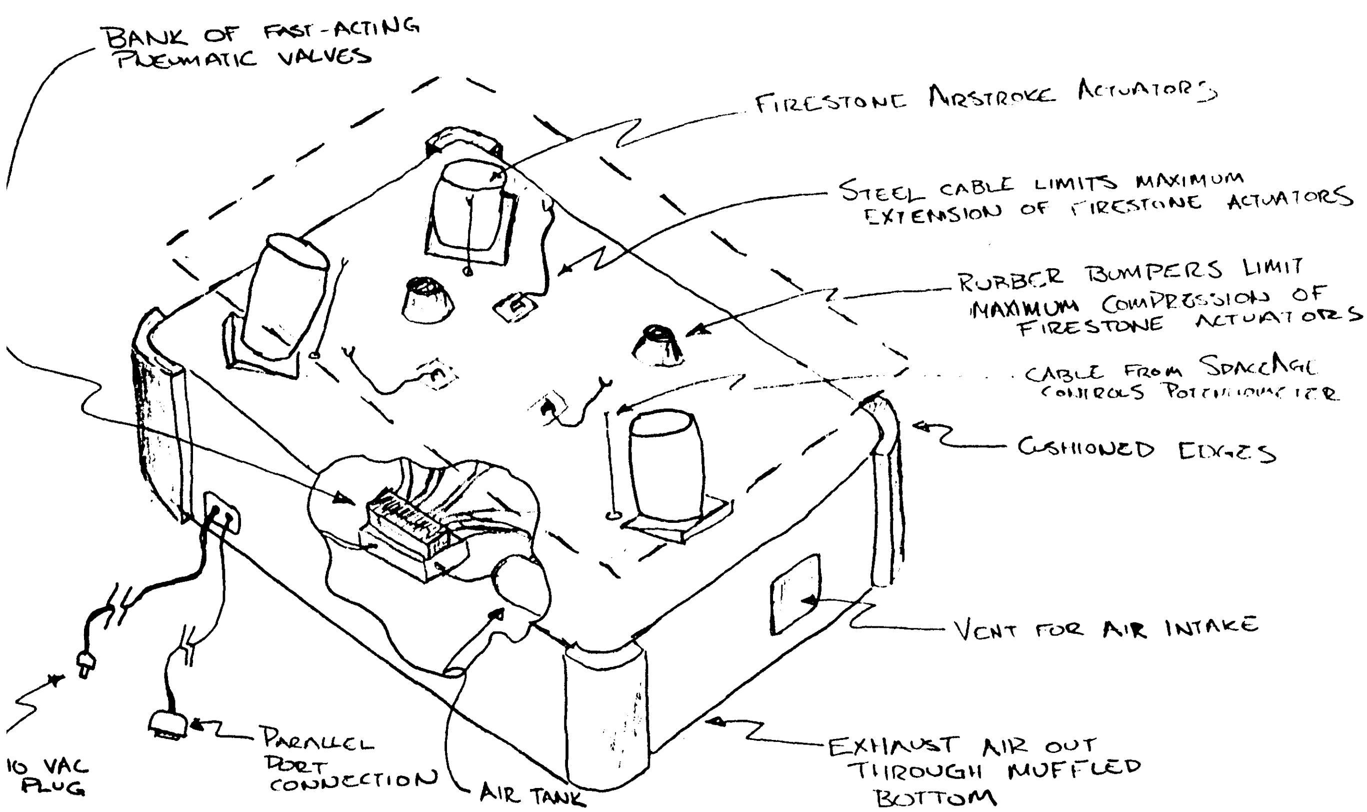
The software companies that write the simulation games need to agree on a universal language and output for motion control simulators as this device, although one of the first on the market, will not be the only one. A standard output location needs to be specified and an ideal location common to all computers would be a parallel port. The parallel port can support communication up to 1 MB/sec, which is more than fast enough for even six or more DOF motion platforms. Most computers will support up to 3 parallel ports without any hassle, and almost all computer users use only 1 of these ports for the printer.

A second parallel port can be purchased for less than $10 and installed in less than 5 minutes. The parallel port output signals could also be used by force feedback input devices and is therefore an ideal output location. Next, a universal language needs to be specified that could be easily used for all types of motion or pseudo motion platforms as well as for force feedback devices. I would propose a system in which a string of numbers is sent at 33 Hz through the parallel port. This string of numbers would be the acceleration values in m/s^2 for the translation axes and rad/s^2 in the rotation axes. Thus the string set might look like (3, 1, 11, 0.3, 0.1, 0.2) which would correspond to (Surge, Sway, Heave, Roll, Pitch, Yaw). These are the X, Y, and Z translation accelerations followed by the rotational accelerations in X, Y and Z. Since the human body cannot feel velocity it is not important to provide this data. With the acceleration data, each motion platform company would be responsible for trying to make the most of their simulator in reproducing the real accelerations as requested by the software. Therefore, each company would need to use different washout filters as continuous accelerations cannot be fully simulated as each simulator has a finite travel length. Perhaps there could also be an initialization string sent over the parallel port such that the maximum accelerations in each axis were known before the washout filter was configured. Further it would be useful to know the maximum position translations and rotations that would be ideally required. In this way, the washout filter for each motion can be configured to better suit each individual program. For example, a driving simulation could closely reproduce the desired motion and still have an extra pitch for the simulation of heave motions. A flight simulation on the other hand, would require a washout filter that would attenuate large pitch acceleration commands. With the initialization commands complete, the motion platform would compute the filters for each axis and try to simulate the requested commands as best as possible. The simulator may not have an axis that motion is requested in and therefore it would be up to the programmers of the motion platform to fake these motions as best as possible. For example, sway can be faked by rolling slightly, surge can be faked by pitching slightly. It is also possible to fake low frequency yaw motions by using only visual cues. High frequency yaw motions might be added by using a limited angle base. This could provide a $\pm 30°$ yaw motion without the problems of continuous rotation. The other motions pitch, roll and heave are difficult to fake with other motions and thus these are the motions that have been chosen for the VirtuaRide project. As an add-on, it would also be possible to add a continuous yaw motion axis for increased realism. This would most likely be a friction drive system and would necessitate the need for slip rings and/or wireless communication devices. This would add considerably to the overall cost and could be pursued at a later stage in development.

For this project, code has been written to demo the system in which an unchanging demo (no user input) is run and the simulator is made to mimic these motions. To make this a commercially viable product, more code would need to be written to take commands from the parallel port and use these commands with washout filters configured by the initial setup information provided over the parallel port. While this is being done, the standard would need to be agreed upon by a majority of software manufacturers. If this can be agreed upon, software companies could start adding this output to their simulation games and those users that have such a system could plug in their system and start playing any of these games with nearly no setup required. Furthermore, a standard output and language such as this would make software support more widespread and the proliferation of a great variety of feedback and motion devices.

The possibility of a G-seat device has been considered but for the average user the added benefit would most likely not be worth the additional cost. However, the thought of adding such a device has made the use of modular components a requirement. If a G-seat could be produced, such a device could be installed inside the motion simulator or used as a stand-alone device. Due to the nature of the parallel port and the universal language, no special connections or changes would be required when upgrading the system from a 3 DOF motion platform to a 4 DOF platform with the G-seat as the fourth degree of freedom.

To add to the realism of the simulation, most cars and planes vibrate at low frequencies usually produced by engine harmonics. These frequencies tend to be greater then 30 Hz and less than 300 Hz. The pneumatic platform is limited to a maximum frequency of roughly 5 Hz, so it would be unable to reproduce these vibrations. Therefore, to reproduce these vibrations, two different approaches could be used. One method would be to use a large subwoofer that would not only produce vibration but also sound. This may be a benefit or a disadvantage, depending on the environment. To use a subwoofer, one would need to have some type of volume control, when it was required that the system not be too noisy. If the volume was turned down, the strength of the vibrations would also be diminished. One other solution would be to use bass shakers. A bass shaker is simply a voicecoil (the same actuator that is used in subwoofers), except instead of moving a large cone back and forth to move air, a heavy mass is moved instead. This would produce more accurate vibrations and could be used without producing much noise. The bass shakers can be purchased for a lower cost than subwoofers, but since they do not produce sound a sound system would also be required. Since the technology of speakers is advancing each day, separating the vibration motions from the sound system seems like a good idea. Again, this is a step that makes the system more modular and easier to be upgraded. One particular advance that would be nice to include would be a speaker system that uses 3D sound. For example, as a user "drove" past another car, he would hear the sound not only change pitch (due to the Doppler effect) but also the sound source would change from in front of him to behind him.



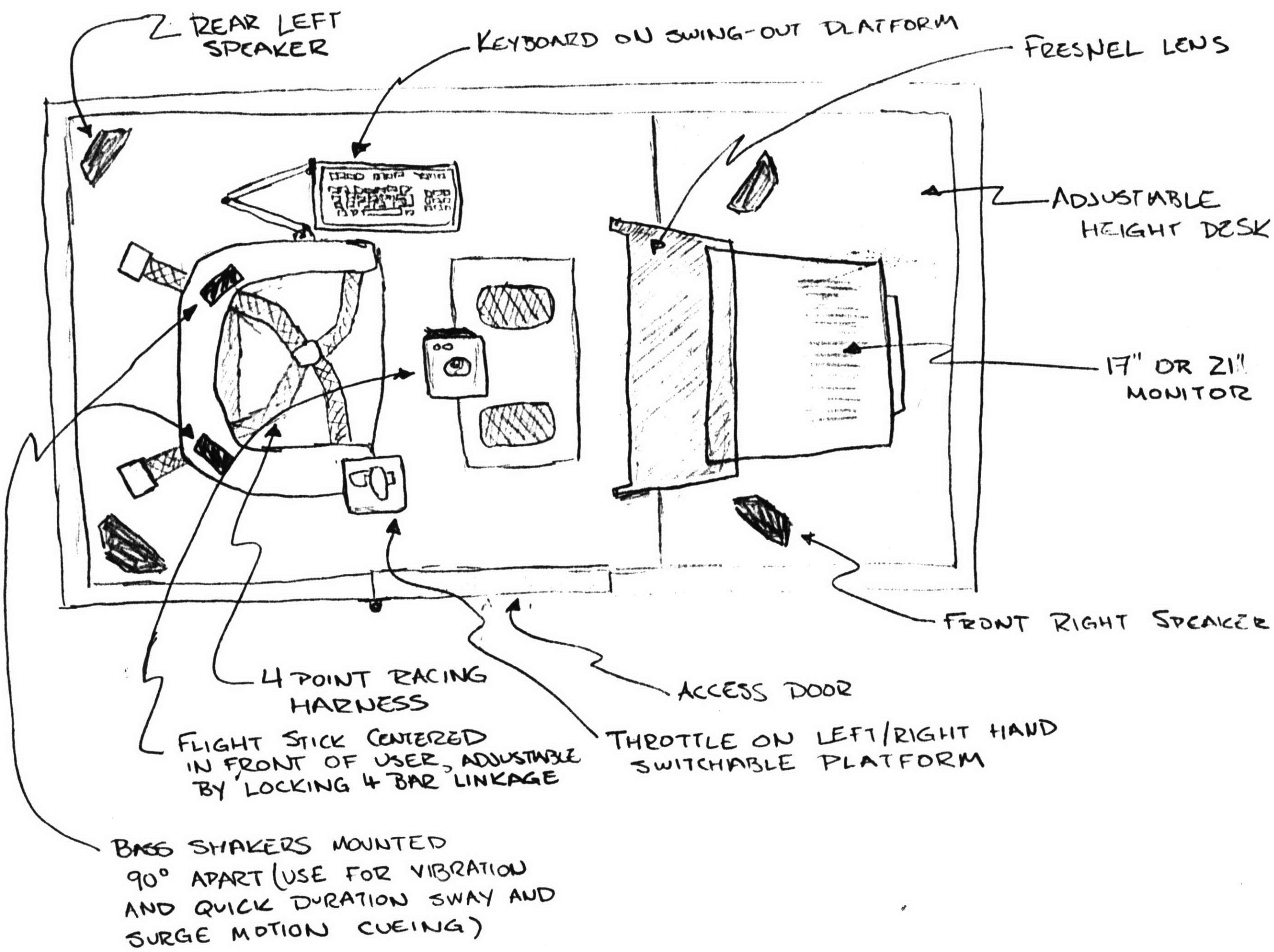
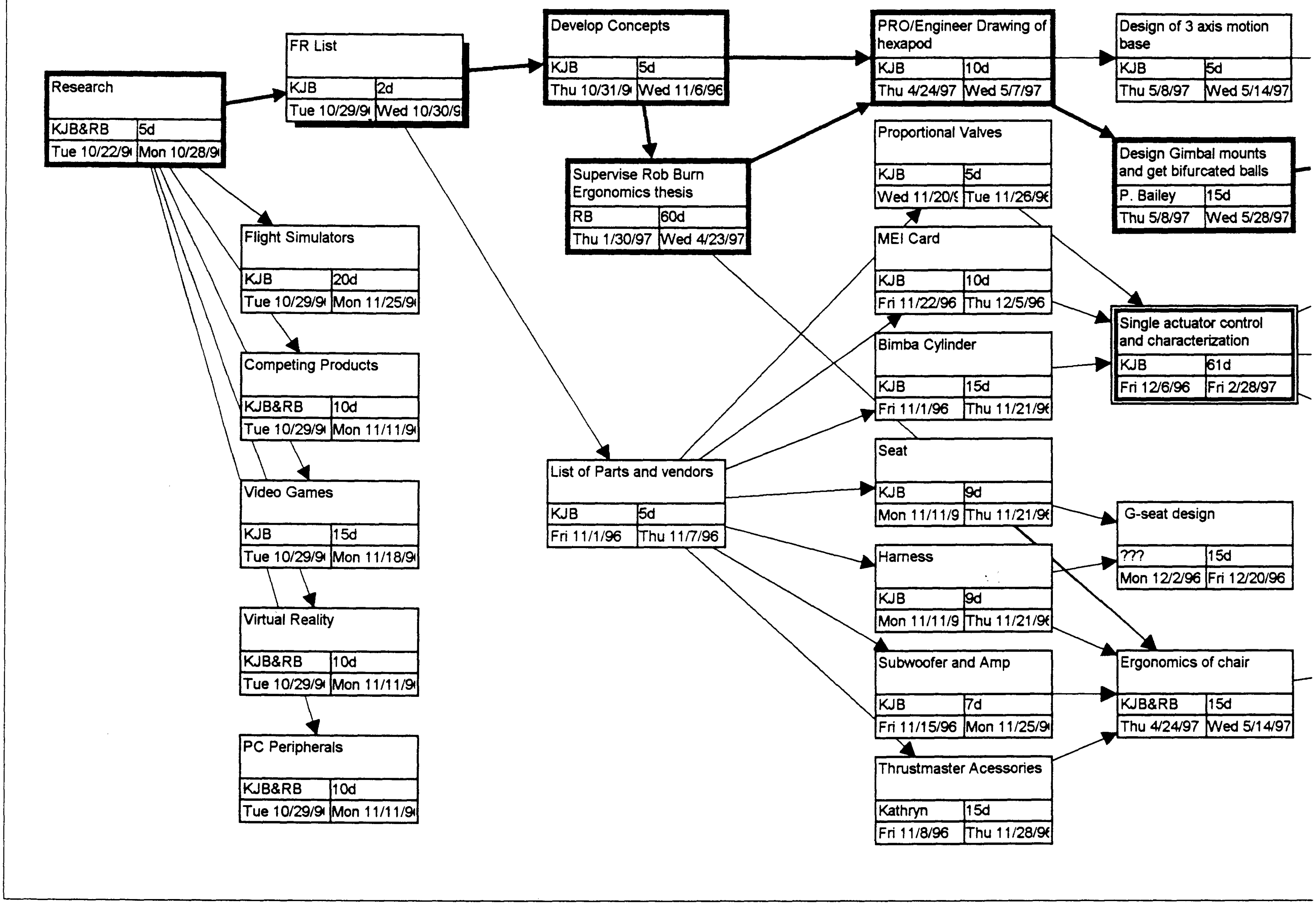


FIGURE 26 – THE VIRTUARIDE PROJECT

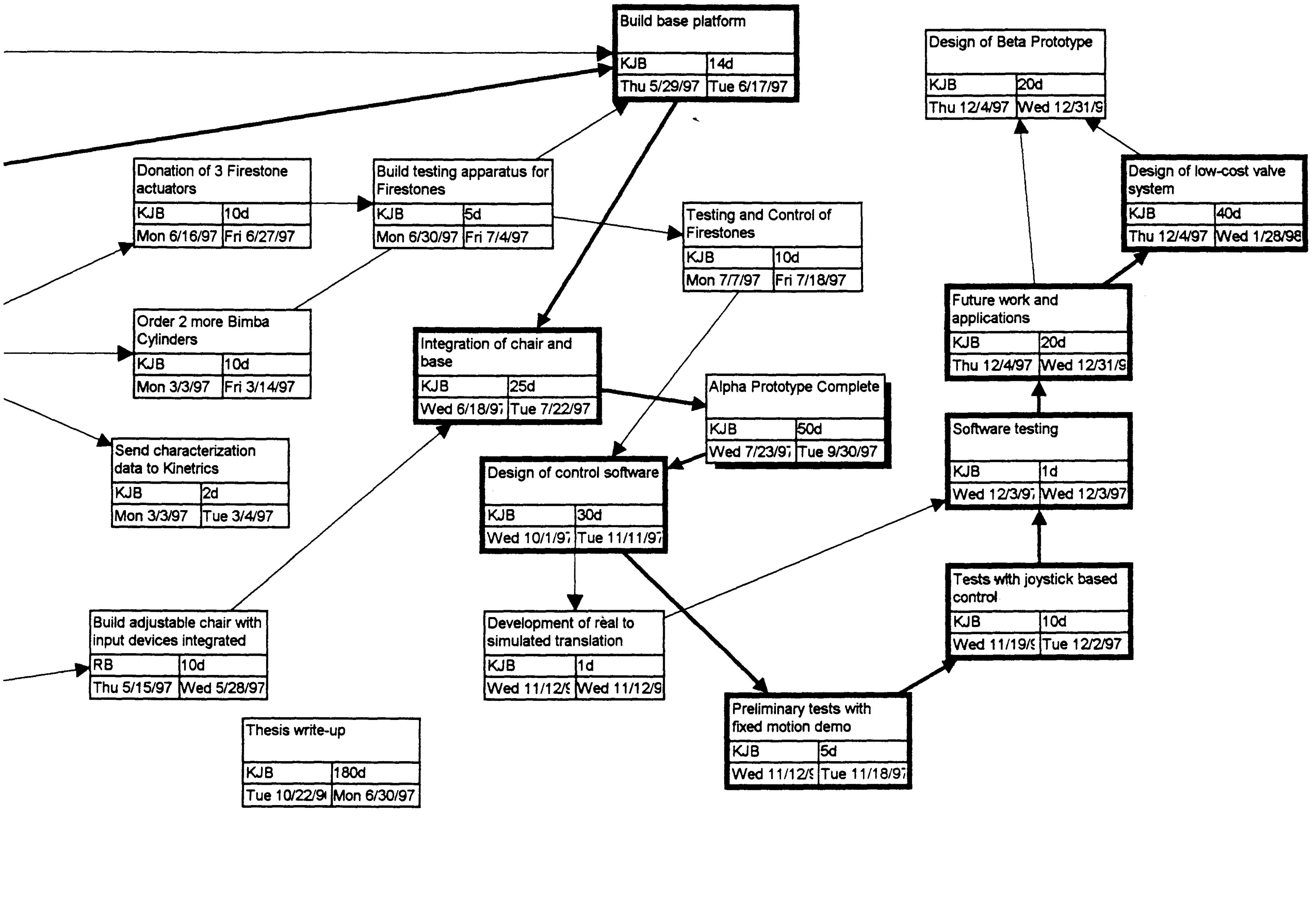
10. Project Planning and Management

This project encompasses a great deal of work and thus we created a team to work on individual sections of the project. To facilitate and coordinate in an organized manner a project plan was required. A PERT chart was made with start and completion dates and who was responsible for each task. This chart can be seen on the next two pages.

Virtua Ride Project Schedule



Virtua Ride Project Schedule



The PERT chart is just a tool to help with the tasks of managing such a project. There are other tools such as Gantt charts and calendar type schedules. It is up to the engineer managing the project to decide which type of scheduling system to use, they are all effective and it is really a personal preference as to which type to use. The PERT chart is nice because the blocks and dependencies from and to each block are easy to follow. In this way, if one task (or block) is delayed, it is very easy to see how it will affect the overall project schedule. It is also useful to find the critical path. The critical path is the route or series of tasks which defines the project completion date. If a task on the critical path is delayed one day, then the overall project will be completed one day later than scheduled. If a task that is not on the critical path, delays do not matter unless they are so long as to define a new critical path. So if a task that is supposed to take 8 days takes 10 days, but the dependencies for that task are not needed for 5 days after the scheduled finish of that task the delay will not affect the project completion date. Only if the task takes more than 13 days (8+5) does the overall project get delayed. In this way a PERT chart is very useful to project managers and engineers.

11. Development

Safety is a major factor if this is to be a commercially viable product. The entire system must be idiot proof and virtually impossible for anyone to sustain any injuries from using the system. This includes all age ranges and body sizes. Some of the safety features that were investigated are: seat belts, head whiplash protection and panic release.

The seat belts are used to prevent the user from being thrown from the chair during motion and also prevent sliding into unsafe positions. The belt system must be secured tightly around the user and hold them in position. The user should not be able to operate the machine if the seat belt system is not properly secured. To this end we chose a 5 point racing harness that would effectively hold the user in place while also adding to the realism. To ensure proper usage of the belt system, two systems were investigated. The first consisted of running a small voltage through the belts and only if all belts were fastened would an electrical connection be made and the user allowed to proceed. This voltage would be 5V and only a few milliamps and thus there is no danger of shock or electrocution. The second system ensures that the belts are properly tensioned. The belts come with adjusting straps but do not ensure proper tensioning. To this end the belt harnesses were spring loaded to provide the proper tension. The seat belts also employ a centrifugal spring ratchet locking mechanism, the same system used in cars.

To prevent neck injuries due to whiplash a helmet and bracing system are used. The helmet is well ventilated yet cushioned to a slight degree. The helmet also adds a certain amount of realism to the simulation. The helmet has an integral neck support. In the future, if true heave and sway motions are added, the need for neck support will become more critical and a method to use an air dashpot damper is being investigated. This would consist of an air damper mounted to the helmet that would prevent rapid jerking motions of the head but still allow all the freedom needed and would not restrict the turning of the head.

Finally, a panic release mechanism is needed in case the user wants to stop or is feeling sick. This system must stop the motion of the platform and bring the system to rest at the "home" position. There could be two different panic buttons. One could be a momentary touch switch located on the handle of the joystick. If the user releases his hand from the joystick the game would stop. This may cause other problems and complaints if the user wants to release his hand for a second but does not want the game to stop. Therefore, a panic button will be employed located just next to the joystick that can be easily pressed at any time but located in such a way that an accidental touching would be improbable.

To weigh the user and thus prevent differences in acceleration for lighter and heavier persons some type of sensor must be employed. A load cell or strain gauge could be used, but this would add another sensor and more control in a system in which low cost is one of the most important goals. Therefore a system is devised which measures the weight of the user without using any additional sensors or controls. In this way the system cost does not change. The method involves a using a pressure regulator. Since a regulator must be included to make sure the system operates at the correct pressure for each person this is a necessary item. At the start of the weighing, the system is not pressurized and the upper platform rests on rubber bumpers. The system is slowly inflated until the position sensors (potentiometers) change values. At this point the pressure increase is stopped and all the weight of the upper platform and user is supported through the air pressure in the three actuators. A simple calculation then finds the weight of the user.

$$W_{user} = P/4(3\pi D2) - W_{platform} \qquad \text{(Eqn. 5)}$$

W_{user} ⇒ weight of user
P ⇒ equilibrium pressure of actuators
D ⇒ diameter of actuators (bore)
$W_{platform}$ ⇒ weight of upper platform with no user aboard

The system would then be brought down to the resting position and the pressure increased a set amount to allow faster movements and quicker filling rates. The optimum offset has not yet been determined but with further testing, it will be possible to determine the best operating pressure for different weight users.

12. Marketing Opportunity

As discussed before, there is a large market for simulation video games and peripherals. This product would be one of the first of a new type in this rapidly expanding market. The biggest obstacle to commercial acceptance is to develop an industry-wide standard for all simulation games such that force feedback devices and motion platforms can use the same set of commands. To develop this language, both software companies and joystick manufacturers need to agree to the standard. If a majority of the manufacturers agree, the smaller companies will be forced to accept the standard. If the standard is designed to be universal for all types of uses, forcing smaller companies to join will not be a problem. For these reasons, the parallel port and a simple acceleration commands in all six axes is proposed. Key companies to target for acceptance of the standard would include: Microsoft, Thrustmaster, CH Products, Microprose, Sega, ID Software, Papyrus and perhaps a few others.

Once the alpha prototype is running well a few demonstration programs should be made. These would simply be hard wired demos which would follow the visual cues of one minute of a video game such as: Mechwarrior, AH-64 Longbow, F-16 Falcon, or others. Once the demonstrations have been made, a few things need to be done. First, a company should be formed, and the device made public. The next step is to start talking with other manufacturers such as Thrustmaster or CH Products and find out if a joint venture can be formed in which all VirtuaRide products are equipped with, for example, Thrustmaster components. Further, talks need to be set up to attempt to approve the universal language through the parallel port. While this work is being done, the alpha prototype should be tested thoroughly and plans for a beta version and low-scale production should be started. Once the beta version is completed and tested, money needs to be raised for tooling, production and assembly of the product. At this point marketing needs to be started to get more public awareness. For low scale production to occur, a large amount of funding is needed and thus either venture capitalists could fund this or a large company might by out the small company and take over the assembly and marketing.

13. Manufacturing Plan

To make this a viable product, at least 500 units need to be sold per year. At production quantities below this, manufacturing cost will be too high to be able to sell the system. For the first generation of sales, the MEI card will be bought in quantity at low cost and a custom made cable will be produced in place of the screw terminals. The cable can be outsourced to a variety of custom cabling companies. The Firestone actuators will be bought in bulk direct from the manufacturer and can be stored on site. A similar but lower cost valve can be bought from FESTO. A small air compressor and tank such as the ones to drive nail guns can be utilized and packaged underneath the base. The lower platform can be constructed of ¾" plywood and the edges reinforced and rounded for safety purposes. All of the wiring, pneumatic lines and air compressor will be housed inside this base and the walls of the base should be lined with some cloth or other sound absorbing material. The upper platform can also be made of wood and painted to look more high-tech. Inside the cockpit will be the chair and harness system and a shelf for the monitor of the user's choice. Also space will be provided on the sides for keyboard, joystick, throttle and other peripherals. Almost all components should be outsourced or purchased of the shelf and assembled at a small plant. If the product does well, funds can be diverted to develop the low cost pneumatic valves and a custom motion control board. Further developments can be pursued as the product gains popularity.

14. Further Research and Development

With the alpha prototype complete, many project spin-offs can start up. Certain integral safety elements need to be made, such as a helmet with a three-axis accelerometer to monitor head motions and stop the simulator if too the user experiences much acceleration or jerk. Other safety features need to be investigated, such as touch sensitive material that would indicate the user has released the joystick or a sensor to verify the user has put on the safety harness and tensioned it properly. Another important task is to optimize the system to minimize costs. Some major cost reducing elements are PWM controlled valves (-$400/axis), a hardwired control board (-$400), a mini-compressor and tank (-$100) and others. The control software, which simulates hard cornering, dives and other motions need to be optimized for the most realistic user feel. An integrated head-mounted display and whiplash prevention system should be investigated as well as high performance sound systems. The actual ergonomics of the interior of the cockpit need to be optimized, and perhaps an entirely integrated system with virtual displays and force feedback devices could be implemented.

The low-cost PWM valves could rival the performance of proportional valves for an order of magnitude less cost. "Do-all" actuators could combine a flexible bellows actuator with a linear potentiometer and a PWM valve mounted directly to the input port. Additionally, the use of a cheap 3DOF platform with high shock resistance and reasonable accuracy would be useful in other fields such as robotic handlers, crash protection seats, and fatigue life testers.

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The Antares Reality Sled

2 Degree-of-Freedom Motion Platform

A MOTION PLATFORM BREAKTHROUGH!

The Reality Sled is a high-performance hydraulic motion platform. An innovative 2 DOF design yields pitch angles from 0 to 20 degrees, and roll angles between +/- 40 degrees at rates up to 60deg/s. The Sled is smooth and fast, with all motions under precise computer control.

Standard Options

The Reality Sled is custom built to your specifications. Standard options include the following:

-  Virtual i-O HMD
- An integrated 3DO Gaming System
- WorldToolKit C library drivers with source code
-  4'x2' passenger carriage with 4-point harness seat

Specifications:

•Weight

The Reality Sled weighs 500 lb. It will support a 350 lb load with a factor of 2 safety margin.

•Floor Plan

The floor plan of the motion platform is 4ft wide by 6ft long, with a 1ft extension in the front center for the pitch cylinder mount. The maximum height of the platform is 4 ft 4 in.

•Pitch

The current system supports pitch angles from 0 to 20 degrees at a maximum speed of 10 deg/sec.

•Roll

The roll angle can currently vary between +/- 40 degrees at a speed of 60 deg/sec. This provides the dramatic movements which are the heart of this platform!

•Power Requirements

The Reality Sled is powered by a standard 110/220VAC wall outlet.

●Control

The platform can be controlled through one of four interfaces:

- A standard PC-compatible joystick,
- Virtual i-O *iglasses!* HMD with head tracking,
- a Nintendo-style hand controller, and
- a standard RS-232 serial interface

The PC joystick is by far the simplest way to interface the platform to an existing joystick-based game. It works by simply connecting a Y-cable between the game machine and the joystick, providing a way for the platform control electronics to simultaneously read the joystick position. It translates this into a proportional motion on the platform.

This way, you can add motion to your game literally without changing a single line of code!

●Payment Terms/Warranty

Payment terms are 50% down and the balance on delivery. University PO's are accepted. The Reality Sled comes with a 1-year parts and 90-day labor warranty.

Motion Platform Solutions *for YOU*

Antares Virtual Reality Systems specializes in inexpensive, high-quality motion platform solutions. We have expertise in both electric and hydraulic motion systems, and in high-precision motor control. If you have a special need for motion, whether it's adding motion to an existing game or building a system from scratch, give us a call. We can create the motion system you need for your special application.

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GYRO-1/PSDD

Portable Spatial Disorientation Demonstrator

Purpose

The GYRO-1 model PSDD is a Portable Spatial Disorientation Demonstrator that simulates vestibular illusions experienced during flight. Trainees sit inside the unit and experience a simulated flight environment.

The GYRO-1 PSDD helps train pilots to recognize, tolerate, adapt to, and perform in physiologically extreme conditions associated with high performance aircraft. Many other flight illusions (e.g. bad weather) can be simulated and the system can be fully customized according to the customer's requirements.

Training objectives include:

- Convince VFR rated pilots to refrain from flying in IFR conditions
- Develop trust in the instruments over vestibular senses during IFR conditions
- Improve instrument flight capability of pilots during disorientation
- Give valuable experience to VFR rated pilots who find themselves flying under IFR conditions

The major benefit of the GYRO-1 PSDD is that it can be used to effectively train pilots safely and economically, since training can be performed without using an actual aircraft.

The Motion System

The unique motion system is a nested 3 axis design, capable of sub-threshold motion in the pitch, roll, and yaw axes. It is driven by electric motors giving smooth, accurate response and is controlled by a single computer system, assuring accurate, repeatable simulation of the disorientation illusions.

The pitch and roll axes are "closed-loop," controlled by the yoke and throttle inside the cockpit. The pilot receives rate of motion cues through the aeromodel and motion algorithms that simulate flight.

The GYRO-1 PSDD can supply rotation at constant speed at both sub- and supra-threshold acceleration. This flexibility gives a convincing demonstration of the inadequacy of the body's semi circular canals as change-in-velocity sensors. The "Pilot-in-the-Loop" feature of the program forces the trainee to relate the demonstration to actual flight situations.

Realistic Cockpit and Instrumentation

- Yoke
- Throttle
- Altimeter
- Transponder
- Turn Coordinator
- Heading Indicator
- Attitude Indicator
- Airspeed Indicator
- Engine Tachometer
- Vertical Speed Indicator

GYRO-1 can be customized to duplicate a specific aircraft model (military or commercial). A forward visual display shows the pilot a computer generated external visual scene. High fidelity engine sounds and instruments respond to pilot activity in real time. With the door closed, the cockpit is "light tight" and extraneous visual and sound cues are eliminated.

VFR-IFR Automated Training Program

During one of the training demonstrations, trainees experience a simulated pre-programmed flight profile under VFR and IFR conditions. The scenario is a cross-country flight which passes through controlled air space. Weather conditions deteriorate from VFR to IFR during the flight. During the demonstration the program instructs the student to perform standard flight tasks, inducing spatial disorientation, demonstrating the dangers of IFR flying. At the end of the demonstration a summary/evaluation can be generated.

Spatial Disorientation Programs

The fully automated demonstration programs guide the student through each lesson using audio instruction and computer control of the motion base and visual scene. The programs can be custom-designed to meet specific user requirements.

PSDD Program Illusions (partial list)

- Leans
- Coriolis
- Autokinesis
- False Horizon
- Oculogyral Illusion
- Somatogyral Illusion
- Nystagmus of Vision
- Runway Approach Illusions

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Reinforce Alternate Training

By demonstrating its debilitating effects, the GYRO-1 increases students' awareness and acceptance of their susceptibility to spatial disorientation. A demonstration ride in the GYRO-1 intensifies the effectiveness of other instructional methods for spatial disorientation training.

Pictured at right, the GYRO-1 cockpit features operating flight controls and a visual display showing flight instruments and an out-the-window scene. Students fly the simulator in real-time, under the guidance of audio instruction provided by an automated training lesson.

GYRO-1 SPECIFICATIONS

Power Requirements: 120 VAC, 20 amps, Single Phase, 60 Hz or 220 VAC, 15 amps, Single Phase, 50 Hz

Portability: Casters, "T" Handle, Leveling Feet

Height: 154.9 cm (61")
Length: 180.3 cm (71")
Width: 137.2 cm (54")
Weight: Approx. 272 kg (600 lbs) – not including optional instructor station

Required Room for Operation: 8 ft x 8 ft floor area, 7 ft ceiling

Aeromodel: Single engine light aircraft. Other options available.

Motion Base

Range of Motion: ±15° Pitch, ±30° Roll, ±360° Continuous Yaw

Angular Velocity: 0-10° per second Pitch, 0-10° per second Roll, 0-15 RPM Yaw

Angular Acceleration: 0-25° per second^2 Pitch, 0-25° per second^2 Roll, 0-10° per second^2 Yaw

Angular Deceleration: Pitch and Roll, same as above; 15° per second^2 Yaw

Subthreshold Motion: All Axes

Pilot-in-the-Loop: Pitch, Roll and Yaw Axes

Additional Features

Visuals: Computer generated, real-time scenery–simulates VFR and IFR conditions–color, 3D graphics, RGB video signal–1024 x 1280 cockpit display resolution

Instructor Control: Hand-held remote control or optional Instructor Console

Communications: Single earpiece with microphone, lightweight, wireless, voice activated, belt battery pack

GAT-II™

GENERAL AVIATION TRAINER

The GAT-II is a multi-purpose basic instrument flight trainer with unique motion and visual systems that simulate the performance of an aircraft. The trainee(s) sits inside the unit and experiences a simulated flight environment. The system can be customized to replicate a variety of aircraft types.

The primary purpose of the GAT-II is to train student pilots in the proper uses of instruments, radio navigation, and instrument flight procedures in a low-cost, realistic training environment. The GAT-II is also capable of situation awareness and spatial orientation training.

The GAT-II familiarizes the pilot with normal and emergency procedures, task saturation, task distraction, channelized attention, and Instrument Flight Rules procedures. As the student progresses through the Basic Flight Instrument Course, the basic motion and visual cues can be altered or deleted to teach the student crucial lessons about using instruments instead of physical senses.

Major Components

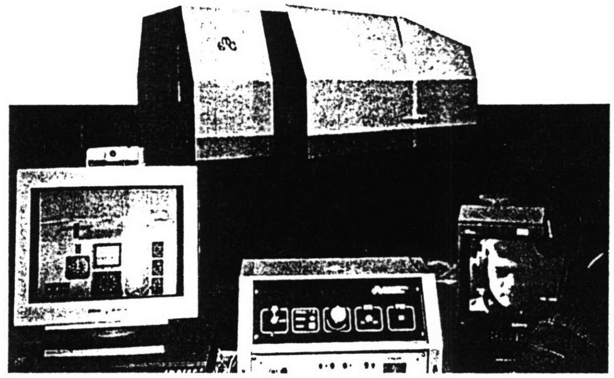
- Cockpit Enclosure
- Computer System
- Instructor Station
- Instrument Display
- Motion System
- Sound System
- Visual System
- Aero-Models

The Motion System

The student station (cockpit) is mounted on a 3 DOF motion base and provides onset and attitude cues to the pilot. The motion base replicates the acceleration stimuli experienced in an aircraft during flight.

The unique motion system is a nested 3 axis design, capable of sub-threshold motion in the pitch, roll, and yaw axes. It is driven by electric motors giving smooth, accurate response and is controlled by a single computer system, assuring accurate, repeatable simulation of training exercises.

The pitch, roll, and yaw axes are "closed-loop," controlled by the yoke, throttle, and rudder pedals inside the cockpit. The pilot receives rate of motion cues through the aeromodel and motion algorithms that simulate flight. To make the motion cues effective, the transport delay time for the motion system is minimized with special software, using flight algorithms and advanced control theory.



Modes of Operation – Training Mode, Profile Mode, Free Flight Mode, Manual Mode, System Readiness Mode.

Realistic Cockpit and Instrumentation

The cockpit of the GAT-II provides selected flight controls and instrumentation representing those normally found in an aircraft. Standard flight controls include yoke, throttle, rudder pedals, and trim controls. Cockpit instrumentation layout can be customized according to specific requirements. High fidelity engine sounds and instruments respond to pilot inputs in real time. With the door closed, the cockpit is "light tight" and extraneous visual and sound cues are eliminated.

The Visual Display System (VDS) contains a database illustrating various types of terrain features and airports. Using computer graphics, the VDS presents a realistic, out the window view of day, dusk, and night scenes along with various weather conditions.

The Navigation System is able to generate range and bearing to ground stations and other data pertinent to the navigation function. NDB, VOR, and ILS stations are modeled. The trainer incorporates the latest Jeppson Navigation database.

The Communications System provides all communication capabilities typically found in aircraft. Provisions are made for instructor monitoring of radio frequency selection. Background and traffic noise as well as radio identification are provided.

The Instructor Station provides the controls, displays, and related facilities required to supervise and monitor the GAT-II operation. After Log-in, the instructor selects the training lesson from the curriculum directory. Once the training session is initiated by the instructor, the lesson can be controlled and monitored and the students performance can be analyzed.

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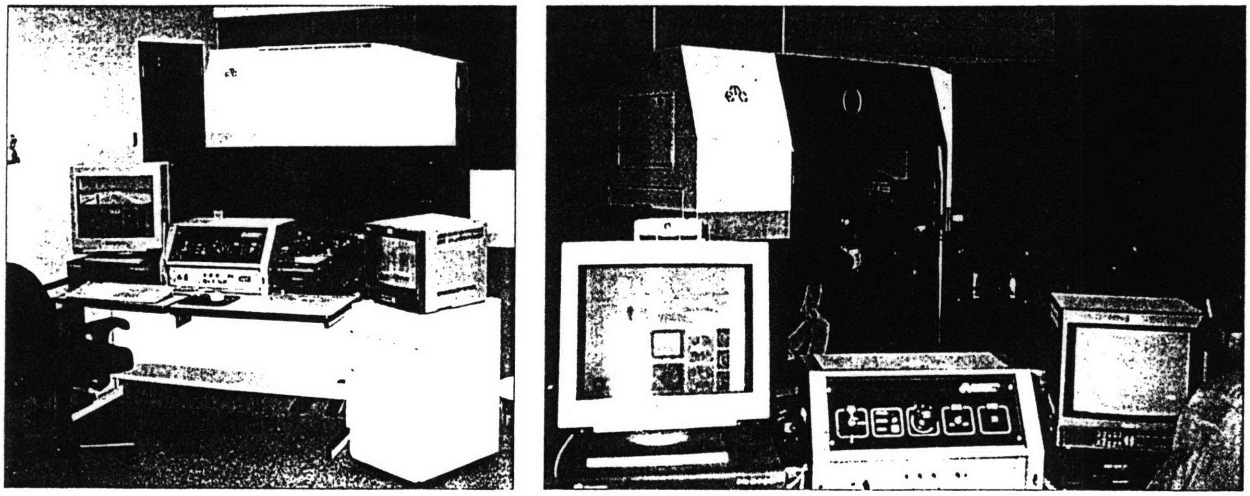


ETC's GAT-II has a dynamic motion base and a simulated cockpit with flight instruments and controls, out-the-window visuals, a navigation system, and a communication system.

GAT-II SPECIFICATIONS

Power Requirements:	220/240, 15 amps, Single Phase, 60 Hz 240 VAC, 15 amps, Single Phase, 50 Hz
Portability:	Casters, Leveling Feet
Height:	190.5 cm (75")
Length:	180.3 cm (71")
Width:	137.2 cm (54")
Weight:	Approx. 386 kg (850 lbs) not including instructor station
Required Room for Operation:	8 ft. x 8 ft. floor area 7 ft. ceiling
Aeromodel:	Commercial or Military Aircraft or General Aviation

Motion Base

Range of Motion:	±15° Pitch ±30° Roll ±360° Continuous Yaw
Angular Velocity:	0–10° per second Pitch 0–10° per second Roll 0–25° RPM Yaw
Angular Acceleration:	0–10° per second^2 Pitch 0–10° per second^2 Roll 0–15° per second^2 Yaw
Angular Deceleration:	Pitch and Roll, same as above 15° per second^2 Yaw
Subthreshold Motion:	All Axes
Closed-Loop Control:	Fully interactive with visual displays and pitch/roll motion

Additional Features

Visuals:	Computer generated, real-time scenery — simulates VFR and IFR conditions — color, 3D graphics, RGB video signal — 1024 x 1280 cockpit display resolution
Instructor Monitoring:	Remote Control Console with station displays
Communications:	Pilot-headset, Instructor-Boom microphone with speaker or headset with microphone, lightweight Optional CCTV system Optional Data Acquisition System

THUNDERSEAT

A 100 watt subwoofer built into the base of the ThunderSeat is coupled to the wave chamber inside this hollow chair. As the diaphragm of this powerful speaker expands, it compresses the air inside the ThunderSeat, generating sympathetic vibrations in the tuned, resonant panels, the result being that the entire chair becomes a rumbling, radiating speaker.

Since low frequency sounds are omnidirectional, you will be immersed in a very realistic *"all around sound"* experience, not only hearing but *FEELING THE SOUND* everywhere you come into contact with the ThunderSeat. And, due to its unique, patented design, an ordinary stereo amplifier can power the ThunderSeat with ease.

"I can't explain in words the submersion I experienced when surrounded by the ThunderSeat setup-- the suspension of belief is just overwhelming. For the most memorable gaming experience, the ThunderSeat is the answer."

Mike Riley, The Ultimate PC Guide, Electronic Games Mangazine

ThunderSeat • $159.95

Affordably priced yet built to the same exacting standards as our military models, the new ThunderSeat Ace is a winner, featuring a comfortable, contoured shape and jet like, reclined seating position. Add the optional side consoles and a keyboard holder to your ThunderSeat and you have the perfect setup for both flight simulation and office work. Compatible with all sound cards and CD-ROMS.

Deluxe Pad Set • $34.00

This one piece, light gray, high tech looking pad is a must-have item for ThunderSeat fanatics who spend hours and even days getting *"good vibrations"* in their ThunderSeats from their favorite sims, movies, or CD's.

ThunderSeat Side Consoles

Per Pair • $119.95

With the slung back, lower sitting position of the ThunderSeat, these free standing platforms are highly recommended for putting your joystick, throttle and mouse at a convenient position. Weighing in at close to 30 pounds EACH, these rock solid platforms give you a real, wrap-around cockpit feel. There are also small slots cut in the front edge so you can conceal your joystick cables inside.

ThunderFlight Rudders

"The best on the market... nothing else come close."

$349.00

With a cast aluminum housing and stainless steel base plate, these are the only rudders on the market that are FAA approved and feature realistic, progressive loading. Perfect for car racing sims too! Complete with "Y" joystick cable.

Consistently rated #1 by reviewers

SuperView 180 Fresnel Lens

$219.95

Just one look at your favorite simulation and you'll realize why Fresnel Lenses are used in all high end simulators. This precision Fresnel Lens is of the highest commercial quality and is the same one used in the visual system of million dollar simulators.

The Lens magnifies the image 30% without distorting it. Thus your 15 inch monitor looks like a virtual 21 inch. More importantly, it also changes the focus point of your gaze from the surface of the screen to infinity. What this means is that instead of looking AT your computer screen, you look THROUGH it, thus generating a more realistic, 3D effect and depth of field.

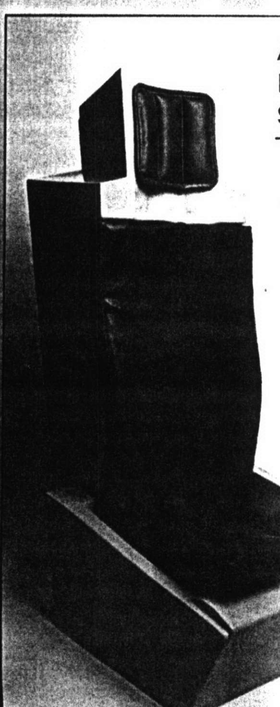
Housed in a black plexiglass, hooded frame that holds the lens at the proper distance and position, the SuperView 180 Fresnel Lens will work with any size monitor up to 21 inches.

Retractable-Tactical Keyboard Holder

$64.00

The problem of where to put your keyboard is over with the ThunderSeat R/T Keyboard Holder. The R/T Keyboard Holder mounts to the left side console by means of four bolts and swings frontwards and backwards like a Dentist's tray. And, if you buy it at the same time you buy the side console, we will predrill the holes for you in the left side console.

ACES II EJECTION SEAT



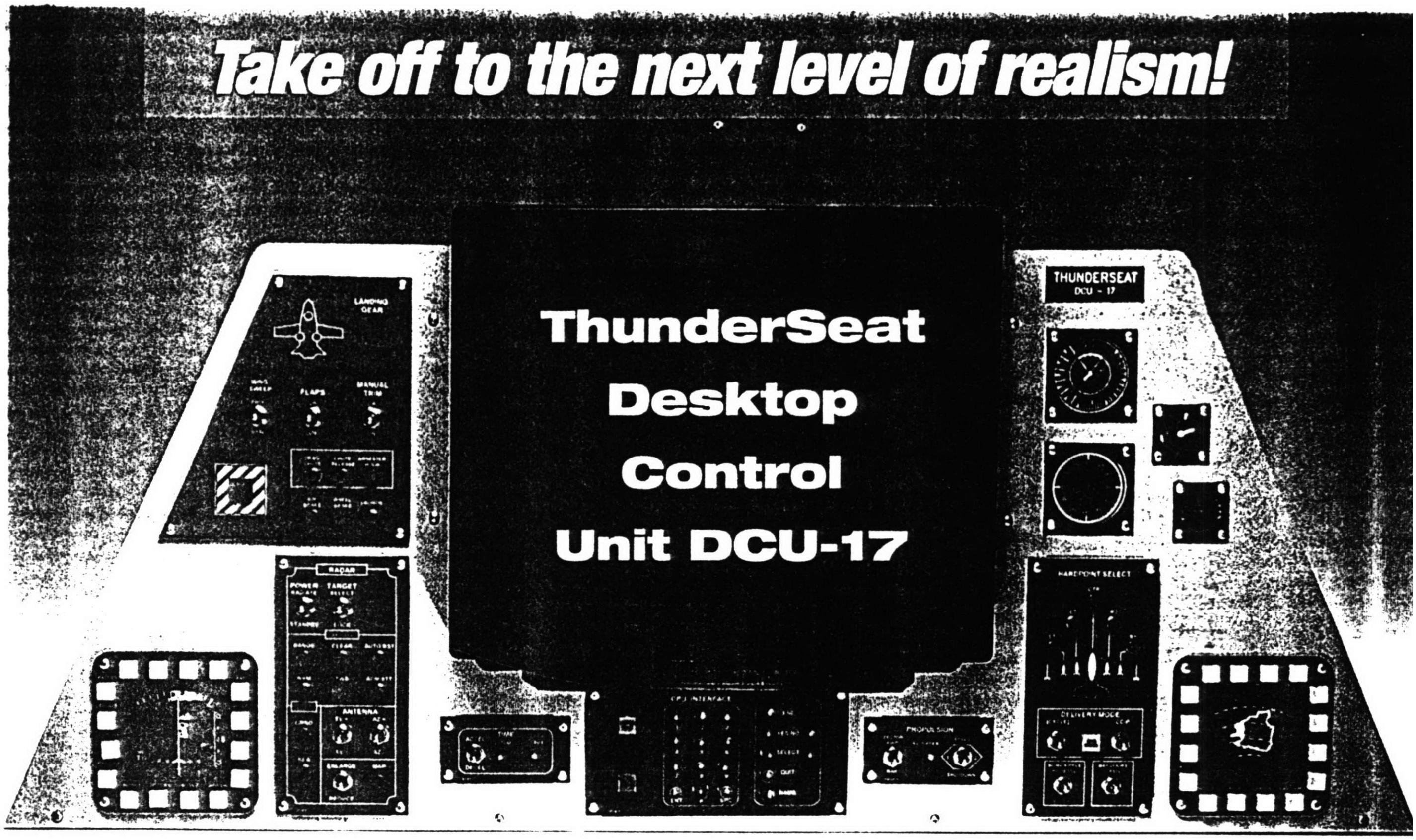
"The motion and acceleration clues the ThunderSeat give you are essentially identical to those you get flying the F-16."

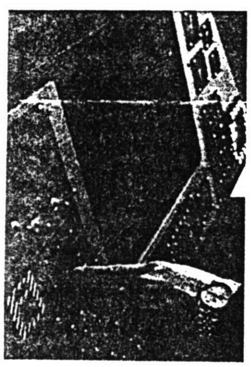
Col. Brent Barker, USAF, ANG.

$695.00

This ThunderSeat ACES II Ejection Seat is the same one we sell to the USAF Airforce. Recreating every dimension of the actual F-16 ejection seat down to the sixteenth of an inch, the ThunderSeat ACES II is as close to the real thing as it gets. And with TWO SVC sonic transducers, the ACES II will definitly blast you into the next dimension of realism.

"ThunderSeats are currently being used by the USAF, the US NAVY, NASA and the Jet Propulsion Laboratory, as well as by major simulator companies such as CAE-LINK, Reflectone, Hughes/Eidetics, and most recently by the McDonald Douglas Training Systems APACHE Helicopter simulator in Mesa, Arizona. ThunderSeats are also being used in a variety of non-military applications from major amusements parks



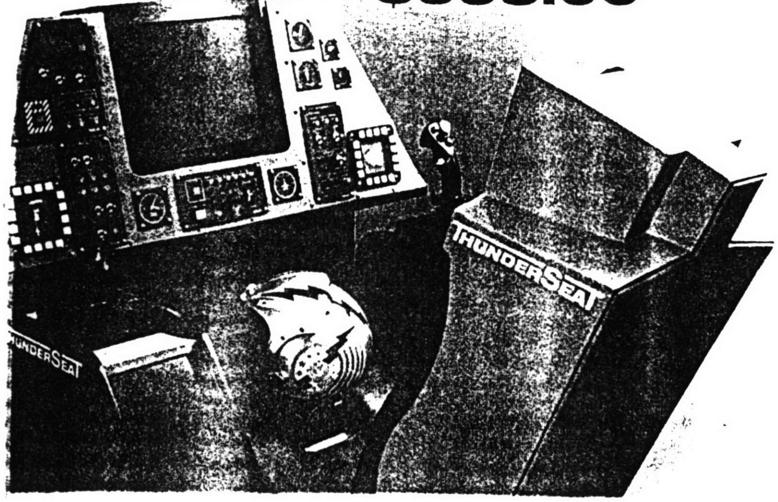


With over 100 real switches and functioning MFD buttons, the Desktop Control Unit (DCU) will turn your desk into an F-16 cockpit. And since its totally reconfigurable for any software, you can switch from game to game and never be confused about keystrokes again. From turning the radios in Microsoft Flight Simulator to radar control in Falcon, the DCU does it all.

With military spec switches and backlit panels, the ThunderSeat DCU is as close as it gets to a real F-16. Separate panels control all aspects of radar, navigation, weapons, views, engine functions, and other vital aircraft functions. The MFD's even have functioning buttons around the edges just like the real thing. Though designed with air combat in mind, since all the switches are programmable through software, you can use the DCU to control any of your favorite sims.

> As games become more sophisticated, so do the keystrokes or combination of keystrokes needed to control them. The multiple buttons on joysticks and throttles help, but after a while remembering what each one does is a little like learning how to play the accordion in the middle of a dogfight.

Only
$995.00

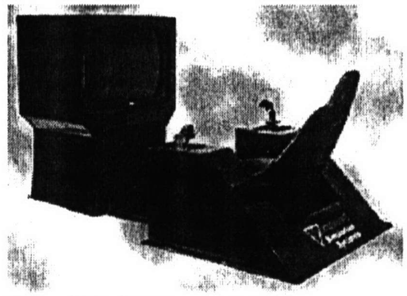


Now you can put away your keyboard for good—
and enjoy the game rather than making it a memory test.

The DCU has its own microprocessor that plugs into the parallel port of your computer and doesn't interfere with your mouse, joystick, keyboard, or rudders. The DCU is designed for monitors up to 21 inches and sells for $995.00 The DCU is available exclusively from ThunderSeat and can be ordered by calling *1-800-8-THUNDER.*

Slide your ThunderSeat up to your desk, put your keyboard away, and take off to the next level of realism with the DCU!

IN-HOME 30 DAY TRIAL



Scalpel-6

Multi-purpose Integrated Flight Simulator

Style

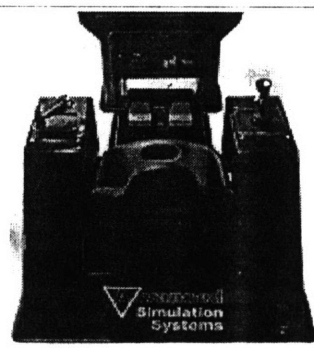
Fly **anything** in this sleek open cockpit design with reclined sonic transducer equipped seat and wrap around black gelcoat fiberglass body. F-16 "HOTAS" flight controls are recessed in the side consoles and hydraulically damped rudder/anti-torque pedals are mounted on a slide adjustable elevated floor.

Comfort

The Scalpel 6 from Advanced Simulation Systems is a pure hands on throttle and stick design so your arms won't have to dance around the cockpit to manipulate switches, dials and levers. Just lean back in the seat and fly without having to remove your hands from the flight controls.
A large 33" 800X600 SVGA Monitor screen provides your virtual cockpit panel and Head Up Display of the outside world.

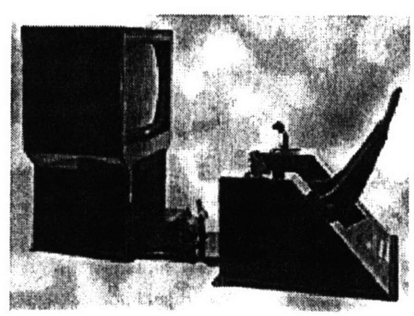
Flexibility

While other physical cockpit simulators become obsolete, this flexible design remains "state of the art" for years to come. Cockpit detail and realism is a pure function of the software only. Easy PC based hardware upgrades will keep the Scalpel 6 on the cutting edge of performance.



Complete and ready to fly!

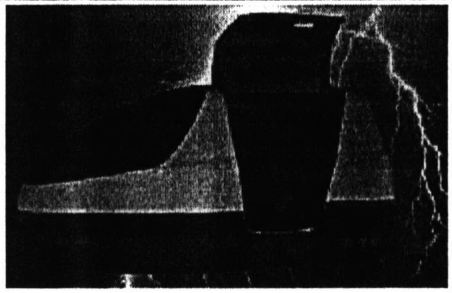
Sensible virtual cockpit design!

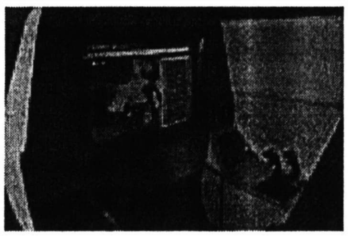


Special Features:

Advanced Simulation Pod

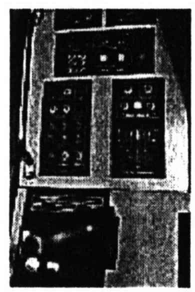
Do you have what it takes to hand fly the space shuttle to a safe touchdown?
The software options are extensive in this ThunderShip Advanced Simulation Pod.





Large Cockpit Interior

Full Cockpit Control Side Panels



Special Features:

- 32" view screen
- Sonic Transducer equipped ACES 2 ejection seat for thunderous vibration
- Gull wing door with gas struts for easy in/out
- "HOTAS" F-16 flight control stick and Throttle Quadrant
- Rugged steel cased hydraulically damped Flight Link rudder pedals
- 2 Multi-function displays
- Full set of interior, backlit control panels
- Over 100 functioning and fully programmable switches
- Exhaust and ventilation system
- Fully configured to fly 2 programs of your choice / Many options available

ASP PRICE

$24,995 US

Weight and Dimensions: 1,185 lbs / Height 60" / Width 53" / Depth 115"

Power requirements: 120 Volt AC 50/60 Hz 15 Amp circuit

Compatible Software: All Programs designed for DOS or Windows®95 operating systems

United States Patent [19]
Neumann

[11] **Patent Number:** **4,551,101**
[45] **Date of Patent:** **Nov. 5, 1985**

[54] **SIMULATOR FOR TRAINING AIRPLANE PILOTS**

[75] Inventor: **Jacques Neumann**, Forest, Belgium

[73] Assignee: **Ateliers de Constructions Electriques de Charleroi (ACEC)-Societe Anonyme**, Brussels, Belgium

[21] Appl. No.: **652,019**

[22] Filed: **Sep. 19, 1984**

[30] **Foreign Application Priority Data**

Sep. 20, 1983 [EP] European Pat. Off. 83201347.8

[51] **Int. Cl.**[4] **G09B 9/08**
[52] **U.S. Cl.** **434/55**
[58] **Field of Search** 434/55, 56, 57, 58, 434/38, 43, 44, 46

[56] **References Cited**

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1545121	5/1979	United Kingdom .

Primary Examiner—William H. Grieb
Attorney, Agent, or Firm—Schwartz, Jeffery, Schwaab, Mack, Blumenthal & Evans

[57] **ABSTRACT**

In a simulator for training airplane pilots comprising a base positioned on the ground (24), a platform supporting an airplane equipment station of which the interior reproduces the interior of a real cockpit (17) and an assembly of jacks (15) and scissors (16) disposed between the base (24) and the platform and actuated by means of a hydraulic control system, the platform is replaced by a cross-braced self-supporting structure in the form of a basket (18), the base of which coincides with the base of the simulated cockpit (17) and the upper edge of which is located approximately at the height of the lower edges of the windows of the simulated cockpit (17), the jacks (15) and the scissors (16) connecting the base to the structure (18) being fixed in at least three places in proximity to the upper edge of the said structure (18) and being directed toward the base (24), mounted on the ground, in spaced apart relationship from said structure.

6 Claims, 2 Drawing Figures

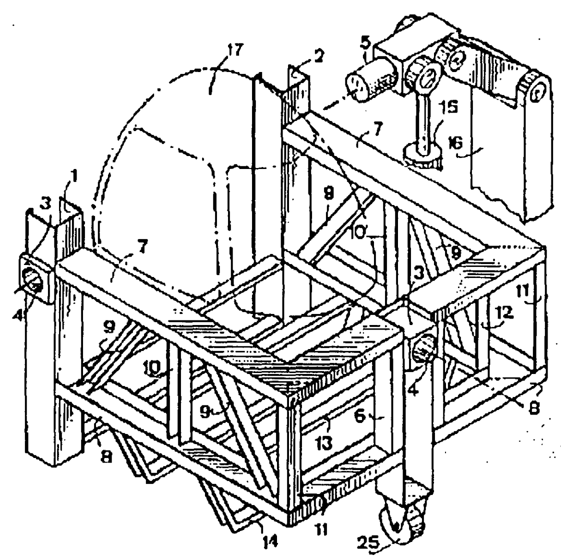
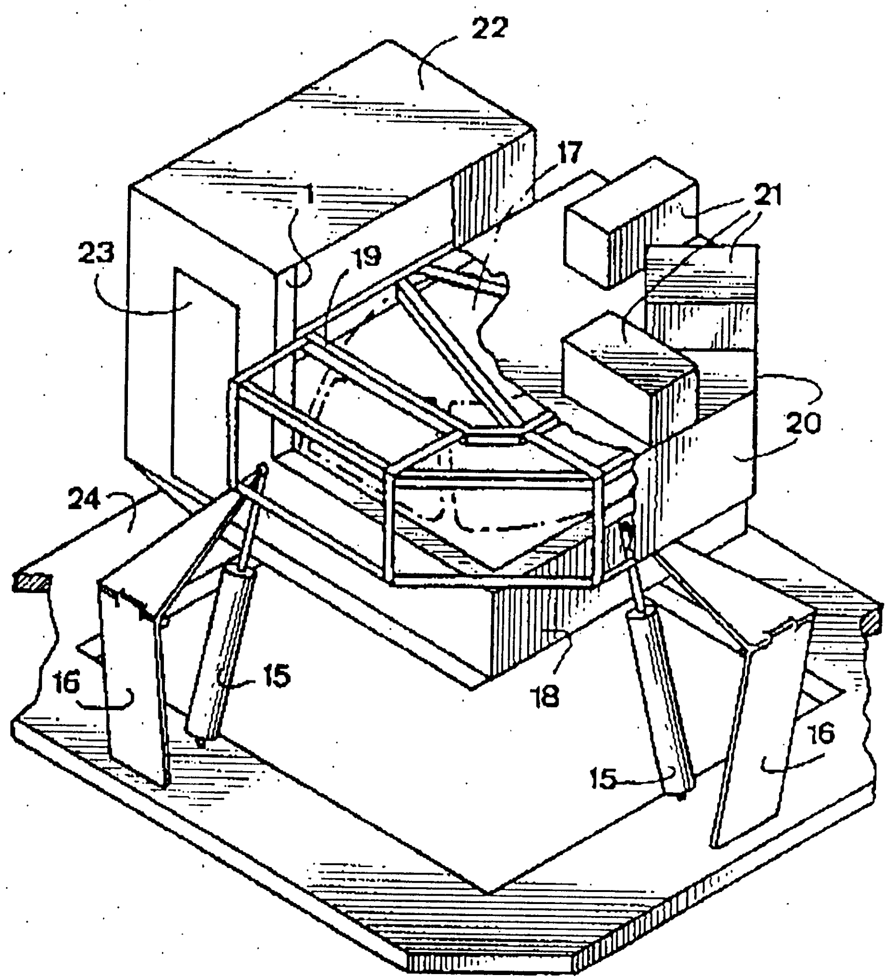


FIG. 2.



United States Patent [19]

Trumbull

[11] **4,066,256**

[45] **Jan. 3, 1978**

[54] **AMUSEMENT RIDE**

[75] Inventor: **Douglas Trumbull**, Santa Monica, Calif.

[73] Assignees: **Future General Corporation; Standard Alliance Industries Inc.**, both of Los Angeles, Calif.

[21] Appl. No.: **632,222**

[22] Filed: **Nov. 17, 1975**

[51] **Int. Cl.**² **A63G 31/16**; G09B 9/00

[52] **U.S. Cl.** .... **272/18**; 35/12 N; 35/12 P

[58] **Field of Search** .... 272/18, 17, 16; 35/11 R, 12 P, 12 N, 12 W, 12 R; 352/85, 239, 240, 131, 132, 40

[56] **References Cited**

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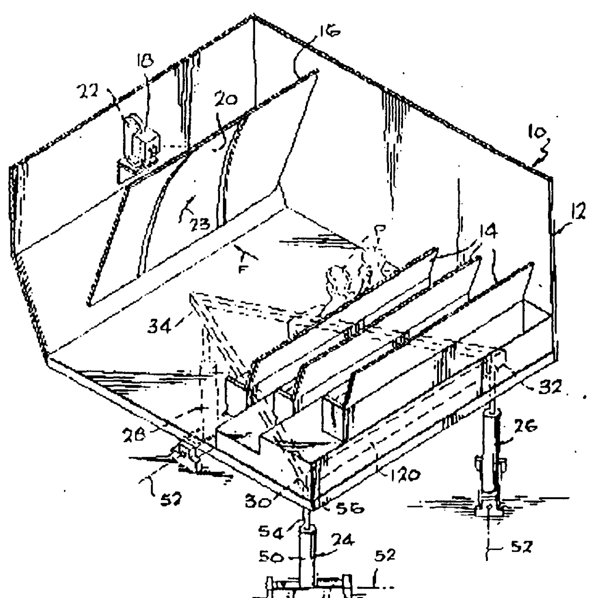
A Platform with Six Degrees of Freedom by D. Stewart Proc. Instn. Mech. Engrs., 1965-1966, vol. 180, Pt. 1, No. 15, pp. 371-386.

Primary Examiner—William H. Grieb
Assistant Examiner—Arnold W. Kramer
Attorney, Agent, or Firm—Lindenberg, Freilich, Wasserman, Rosen & Fernandez

[57] **ABSTRACT**

A relatively inexpensive and compact ride for an amusement park and the like, which creates the illusion that the passengers are seated in a rapidly maneuvering vehicle, by applying forces to the passenger in synchronism with the display of a motion picture image. The apparatus includes a passenger-holding frame which has three locations resting on hydraulic rams that can tilt the frame or move it up and down, and a film projector and viewing screen connected to the frame to move with it. When the motion picture simulates the view from a vehicle that is turning to the right, the rams are operated to tilt the vehicle to the left, to simulate the centrifugal forces that would result from a vehicle turning to the right. When the motion picture indicates forward acceleration, the vehicle is tipped backwardly. When the motion picture indicates vertical acceleration, the rams are rapidly moved up or down.

2 Claims, 10 Drawing Figures



United States Patent [19]

Pancoe

[11] 4,019,261

[45] Apr. 26, 1977

[54] MOTION SYSTEM FOR A FLIGHT SIMULATOR

[75] Inventor: Edward G. Pancoe, Chenango Forks, N.Y.

[73] Assignee: The Singer Company, Binghamton, N.Y.

[22] Filed: May 9, 1975

[21] Appl. No.: 576,092

[52] U.S. Cl. .... 35/12 P; 248/373
[51] Int. Cl.² G09B 9/08
[58] Field of Search .... 35/12 K, 12 P, 12 E, 35/12 S, 12 W; 46/1 B, 1 H; 248/163, 188.1, 276, 277, 371, 373, 376; 272/1 C, 31 A, 31 B

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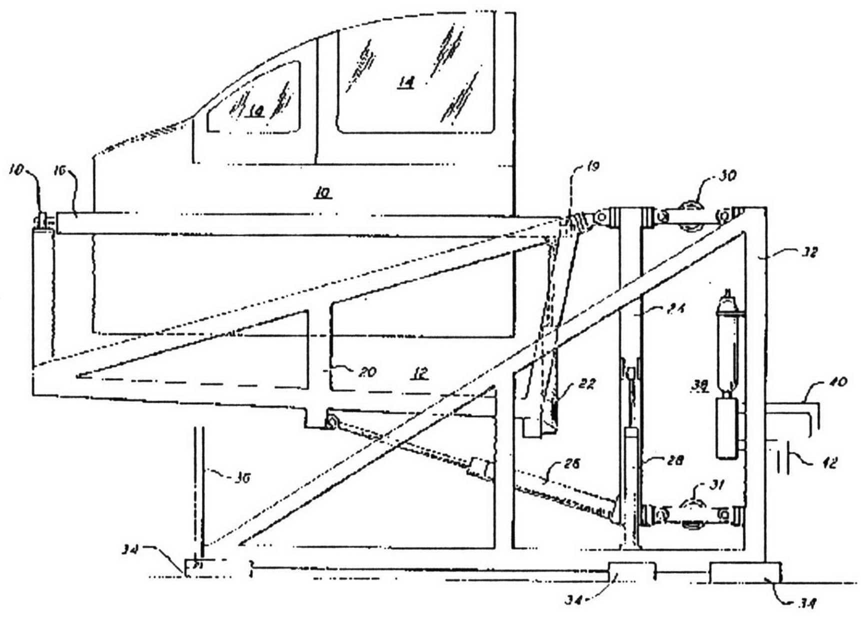
3,619,911	11/1971	Pancoe	35/12 P

Primary Examiner—Richard C. Pinkham
Assistant Examiner—Vance Y. Hum
Attorney, Agent, or Firm—Jeffrey Rothenberg; James C. Kesterson

[57] ABSTRACT

A compact, cascaded three degrees of freedom (DOF) motion system for providing roll, pitch and heave movement to a cockpit of a flight simulator. The cockpit is nested within a rotatable roll frame which is gimbaled within a pitch frame. The pitch frame is pivotally connected at its rear to a vertically disposed and translatable heave frame. A pair of heavy, torsionally rigid, horizontally disposed, torque tubes in a four-bar parallelogram linkage arrangement serve to connect the heave frame to a fixed base frame and to ensure parallel movement of said heave frame. Servo actuators connected to each of the roll, pitch and heave frames permit simultaneous, independent three-axis motion. Balance actuators, frame locking mechanisms, as well as other safety features, ensure failsafe operation of the improved motion system.

17 Claims, 5 Drawing Figures



United States Patent [19]

Lam et al.

[11] **Patent Number:** **4,576,577**

[45] **Date of Patent:** **Mar. 18, 1986**

[54] **BLENDED MODE CONCEPT FOR CONTROL OF FLIGHT SIMULATOR MOTION SYSTEMS**

[75] Inventors: **Wim J. Lam**, Apalachin, N.Y.; **Luitzen Devries**, Amstelveen, Netherlands; **Gordon M. McKinnon**, Montreal; **Jean J. Baribeau**, St. Laurent, both of Canada

[73] Assignee: **CAE Electronics, Ltd.**, Montreal, Canada

[21] Appl. No.: **486,426**

[22] Filed: **Apr. 25, 1983**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 217,701, Dec. 18, 1980, abandoned.

[51] Int. Cl.[4] **G09B 9/08**

[52] U.S. Cl. **434/58**

[58] Field of Search 434/55, 56, 57, 58, 434/59, 46, 49

[56] **References Cited**

U.S. PATENT DOCUMENTS

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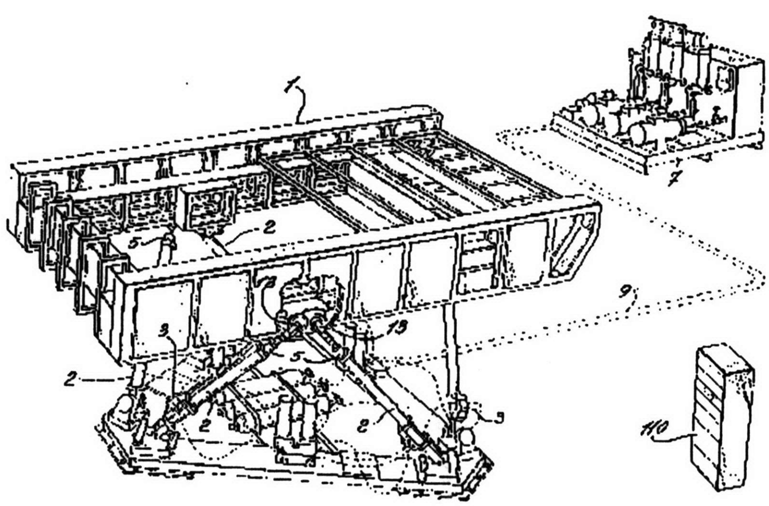
Primary Examiner—William H. Grieb
Attorney, Agent, or Firm—Fishman & Dionne

[57] **ABSTRACT**

The invention relates to a motion simulator system, for example, a flight simulator system. In accordance with the invention, the system is driven by command signals representing both position and acceleration, and a circuit is provided to process and combine the signals to provide a system command signal. High frequency position command signals, and low frequency acceleration command signals, are eliminated by their drive circuits, and all command signals are varying electrical voltages.

8 Claims, 2 Drawing Figures



US005453011A

United States Patent [19]

Feuer et al.

[11] **Patent Number: 5,453,011**

[45] **Date of Patent: Sep. 26, 1995**

[54] **FLIGHT SIMULATOR**

[76] Inventors: **Eduard Feuer**, 1551 Raymond Ave., Glendale, Calif. 91201; **Ronald L. Brown**, 9373 Avalon Rd., Phelan, Calif. 92371

[21] Appl. No.: **75,695**

[22] Filed: **Jun. 10, 1993**

[51] **Int. Cl.**^{6} **G09B 9/12**

[52] **U.S. Cl.** **434/38**; 434/55; 434/30

[58] Field of Search 424/29, 30, 38, 424/43, 51, 55, 58

[56] **References Cited**

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Primary Examiner—Gene Mancene

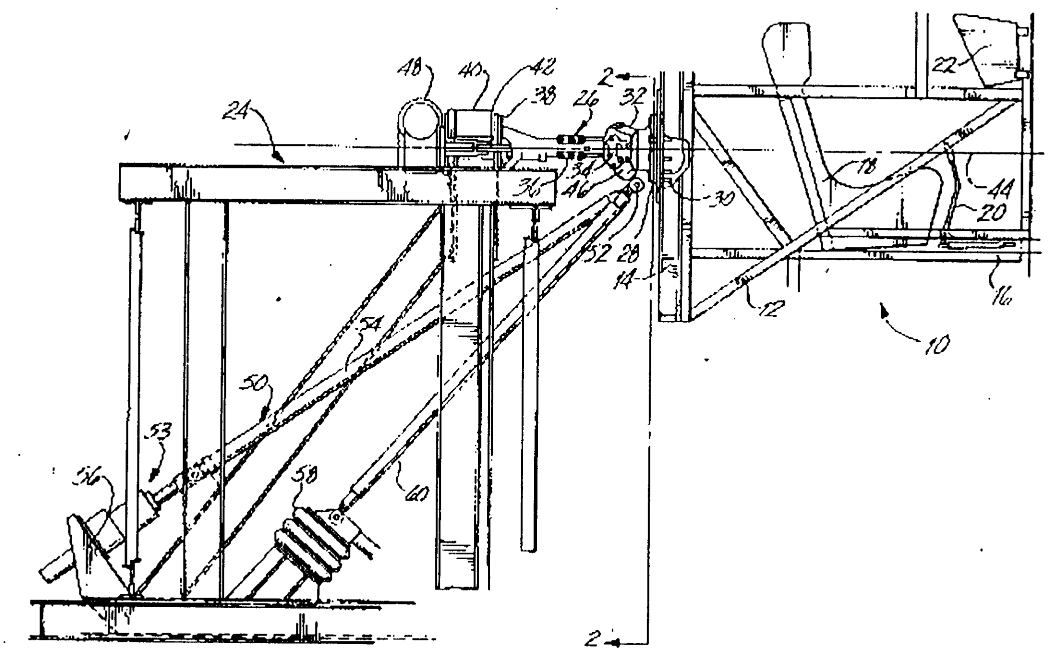
Assistant Examiner—Jeffrey A. Smith

Attorney, Agent, or Firm—Christie, Parker & Hale

[57] **ABSTRACT**

A flight simulator for amusement rides simulating aircraft or space flight with visual presentations and motion having an operator station attached to a structural support frame through an articulating member providing unlimited angular rotation about a roll axis and limited angular rotation about a pitch axis.

7 Claims, 3 Drawing Sheets



United States Patent [19]

Letovsky et al.

[11] **Patent Number: 4,887,967**

[45] **Date of Patent: Dec. 19, 1989**

[54] **HIGH PERFORMANCE MOTORCYCLE SIMULATOR**

[75] Inventors: **Howard Letovsky**, Los Angeles; **Bernard Fried**, Beverly Hills, both of Calif.

[73] Assignee: **Bernard Fried Racing Enterprises, Inc.**, Beverly Hills, Calif.

[21] Appl. No.: **324,172**

[22] Filed: **Mar. 16, 1989**

[51] **Int. Cl.**[4] **G09B 9/04**
[52] **U.S. Cl.** **434/61**
[58] **Field of Search** 434/61, 55, 56, 57, 434/58

[56] **References Cited**

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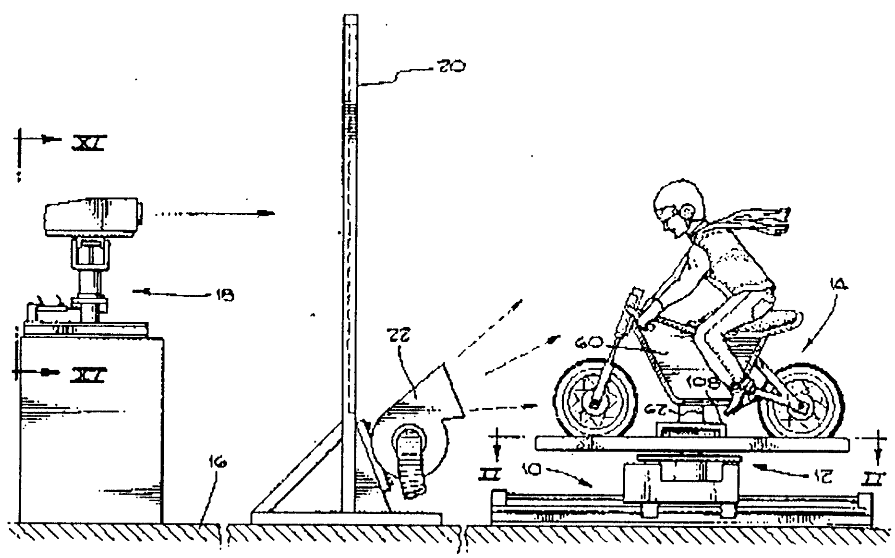
Primary Examiner—William H. Grieb
Attorney, Agent, or Firm—Poms, Smith & Rose

[57] **ABSTRACT**

A motorcycle simulator which is capable of providing six degrees of movement freedom to realistically simulate the sensory cues experienced while operating a high performance motorcycle.

27 Claims, 7 Drawing Sheets



US005366375A

United States Patent [19]

Sarnicola

[11] Patent Number: 5,366,375

[45] Date of Patent: Nov. 22, 1994

[54] MOTION SIMULATOR

[76] Inventor: John F. Sarnicola, R.D. 1, Box 379 B, Gratsinger Rd., Binghamton, N.Y. 13903

[21] Appl. No.: 881,511

[22] Filed: May 11, 1992

[51] Int. Cl.[5] G09B 9/00

[52] U.S. Cl. 434/37; 434/29; 434/55; 434/58; 472/1

[58] Field of Search .... 434/29, 33, 37, 43, 434/45, 55, 58, 62-64, 67-69, 30; 364/578; 244/75 R; 472/1, 3, 14, 16-20, 27-37, 39, 44-47

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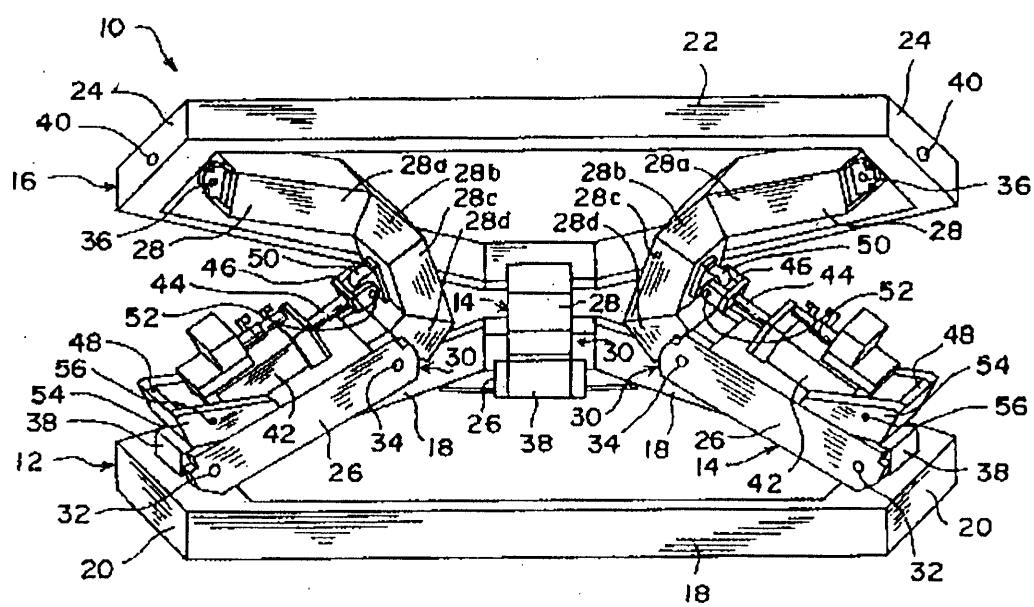
Primary Examiner—Richard J. Apley
Assistant Examiner—Glenn E. Richman
Attorney, Agent, or Firm—William L. Klima

[57] ABSTRACT

A motion simulator comprising a base support connected to a motion platform by hinged legs. The motion simulator is provided with an actuator for moving the motion platform relative to the base support. Preferably, each leg is defined by a lower leg portion and an upper leg portion with a separate actuator connecting the leg portions for providing actuating legs that also stabilize movement of the motion platform.

17 Claims, 15 Drawing Sheets



US005509631A

United States Patent [19]

De Salvo

[11] Patent Number: 5,509,631

[45] Date of Patent: Apr. 23, 1996

[54] THREE AXIS MOTION PLATFORM

[75] Inventor: Thomas De Salvo, Ellicott City, Md.

[73] Assignee: Ridefilm Corporation, South Lee, Mass.

[21] Appl. No.: 130,507

[22] Filed: Oct. 1, 1993

[51] Int. Cl.^{6} A47G 29/00

[52] U.S. Cl. 248/370; 248/371; 248/429; 434/55; 472/59

[58] Field of Search 248/176, 178, 248/183, 184, 913, 370, 371, 424, 429; 297/344.16, 344.17; 182/131, 141, 148; 434/55, 29; 472/59, 60, 61

[56] References Cited

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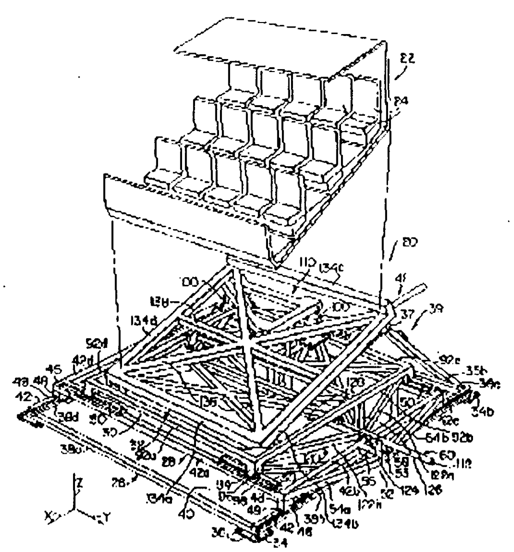
Primary Examiner—Ramon O. Ramirez
Assistant Examiner—Korie H. Chan
Attorney, Agent, or Firm—McCormick, Paulding & Huber

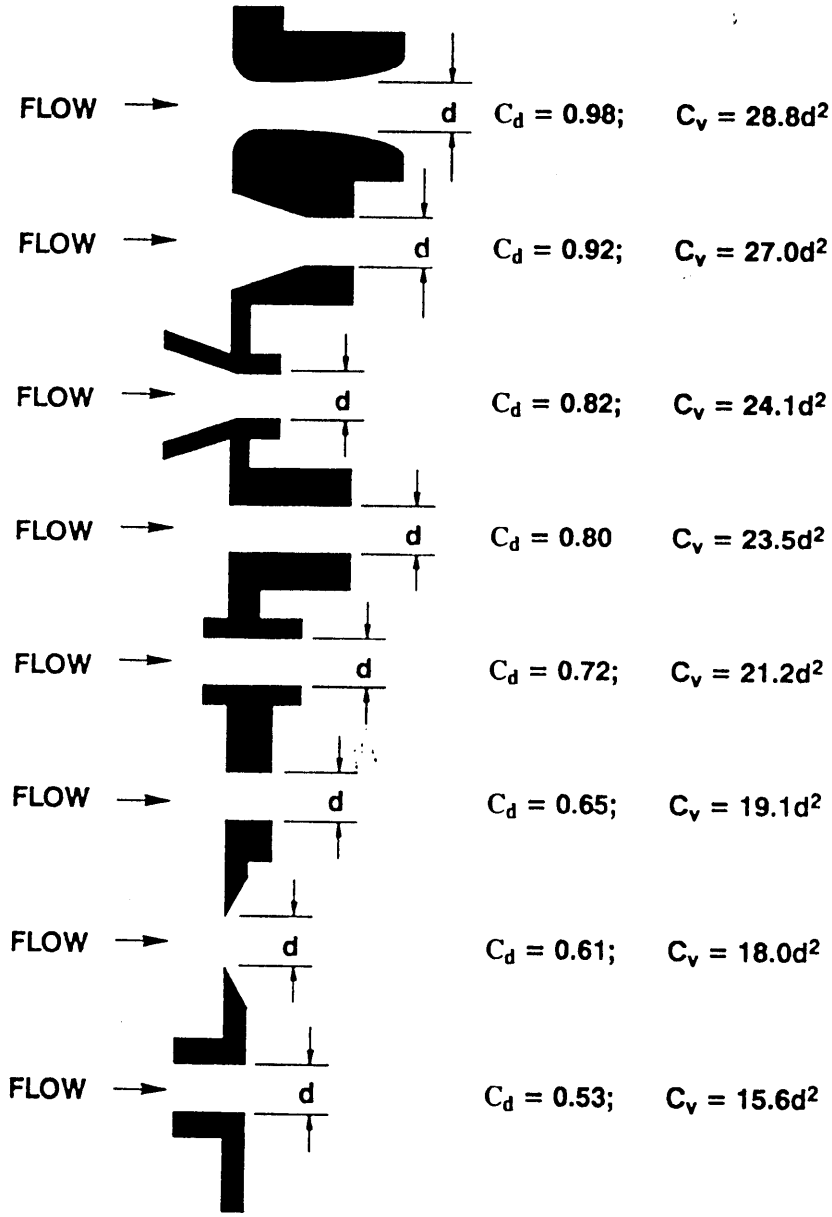
[57] ABSTRACT

A motion platform that is displaceable along three axes includes first, second and third carriage assemblies. There is an apparatus connected to each of said carriage assemblies for linearly displacing each of the carriages along a single planar axis. Therefore, the first carriage assembly is linearly displaceable along a first plane, the second carriage assembly is linearly displaceable along a second plane that intersects the first plane, and the third carriage assembly is linearly displaceable along a third plane that intersects at least one of the first and second planes. Each of the carriage assemblies is comprised of a circumferential array of frame members that define a substantially planar parallelogram configuration having a substantially open central portion, with the carriage assemblies being arranged in a nested array.

17 Claims, 4 Drawing Sheets

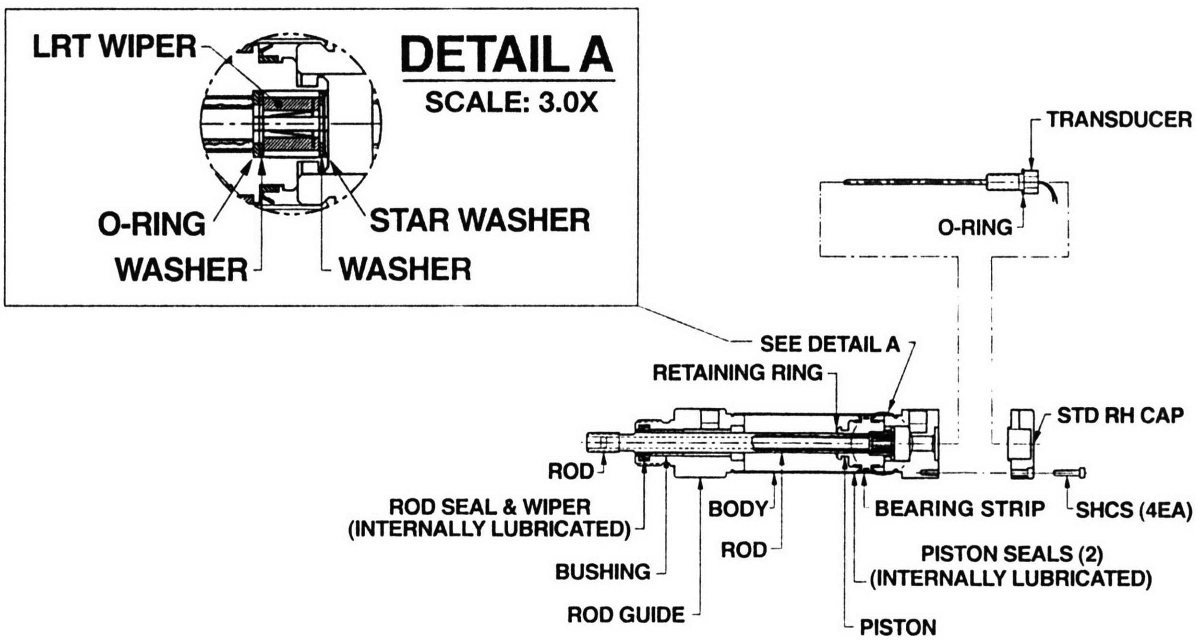


Appendix C – Discharge Coefficients for Various Orifice Shapes



ALL OPENINGS = d" (diameter)

How it Works



ıe *Bimba Position Feedback Cylinder* contains a near Resistive Transducer (LRT) or potentiometer ounted in the cylinder rear head. The LRT probe, hich has a resistive element on one side and a ›llector strip on the other, is inside the cylinder rod. A iper assembly is installed in the piston. As the piston oves, an electrical circuit is created between the re-stive element and collector strip. The resulting voltage directed externally via wiring. The output voltage is oportional to the wiper position on the resistive ement, which allows the cylinder position to be etermined.

›r example, in a 12-inch stroke cylinder, the output ıltage would be 0 VDC when fully retracted and 10)C when fully extended. Voltage readings of 2.5 and 333 VDC would indicate cylinder extensions of 3 ches and 7 inches.

ıe accuracy of an LRT is determined by three factors: solution, linearity and repeatability.

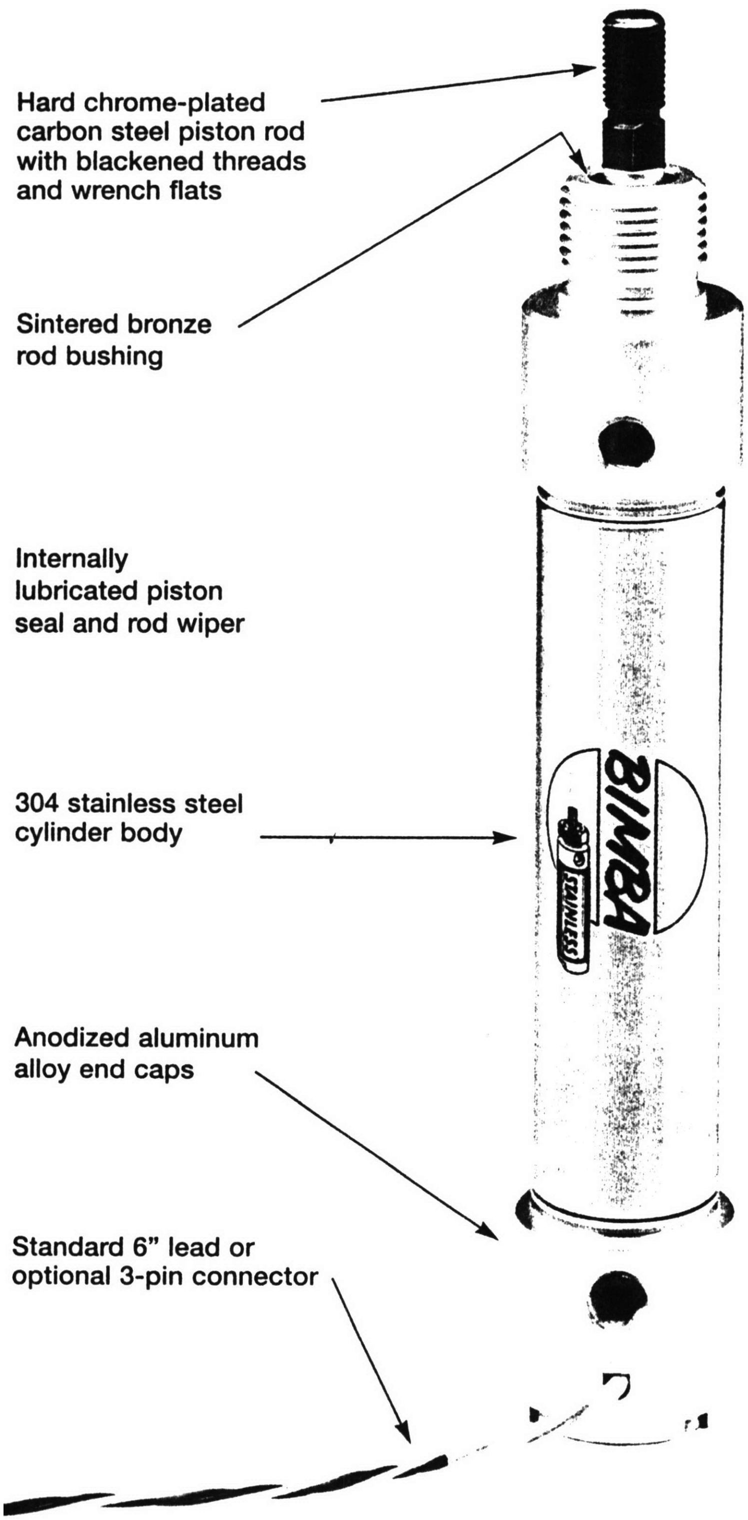
Resolution refers to the smallest change that can be detected on the LRT. The Bimba LRT has infinite resolution, and can be divided into as many parts as the electronics allow. For example, with a 12-bit, 4096-part controller, the stroke could be divided into 4096 parts. When 10 VDC are placed on a 10" cylinder, the smallest detectable increment would be 10 VDC ÷ 4096 = 2.4 millivolts or 0.0024". Resolution is stroke sensitive, i.e., the longer the stroke, the less resolution.

Linearity refers to the maximum deviation of the output voltage to a straight line. The Bimba LRT's linearity is ± 1 percent of stroke.

Repeatability is the ability of the LRT to provide the same output voltage relative to a unique cylinder position each time the cylinder is cycled. Repeatability of the Bimba Position Feedback Cylinder is ± 0.001".

The Bimba Position Feedback Cylinder provides continuous position sensing in a lightweight, small-bore air cylinder.

Ideal for applications where magnetic position sensing is impractical, where variations in cylinder speed or stroke are needed, or where an operation requires constant monitoring of cylinder position.



ADVANTAGES

- Highly accurate: infinite resolution, linearity of ± 1 percent of full stroke, ± 0.001" repeatability
- Less than 0.75" longer than conventional magnetic piston cylinders
- Reduces weight and size
- Repairable
- Internally-lubricated seals
- Standard wipers and piston bearing strips for long cylinder life
- Optional bumpers
- Choice of standard 6" lead wire or 3-pin connector
- Electronic controllers available for dual set point and scalable analog output applications
- Rear head cap can be rotated for optimal positioning of lead or connector

CAD Drawings

CAD drawings of all PFC models are available on CD-ROM.
Contact your local stocking Bimba distributor to order.

For Technical Assistance:
800-44-BIMBA (800-442-4622)
(United States, Mexico & Canada)

Engineering Specifications

Repeatability:	±0.001"
Nonlinearity:	± 1 percent of full stroke
Resolution:	Infinite
Signal Input:	0 to 10 VDC
Signal Output:	0 to 10 VDC (1 Mohm impedance min. required)
Maximum speed:	50 in./sec.
Rated Life of Cylinder:	1,800 miles of travel
Rated Life of Probe:	7,500 miles of travel
Nominal Resistance Rating:	1 Kohm/in
Pressure Rating:	150 psi
Temperature Rating:	0° to 160° F
Interface:	6" leads (standard) or 3-pin connector
Cylinder Body:	304 stainless steel
Piston Rod:	Hard chrome-plated carbon steel with blackened threads and wrench flats
Rod Bushing:	Sintered bronze
End Caps:	Anodized Aluminum alloy
Piston Seal:	Internally lubricated urethane
Rod Wiper:	Internally lubricated Buna N

ESTIMATED CYLINDER WEIGHTS (LBS)					
	1-1/16"	1-1/2"	2	2-1/2"	3
PFC-	0.44	0.88	2.02	2.78	3.62
PFC-X	0.49	0.96	2.14	2.96	3.85
PFC-BF	0.54	1.07	2.28	3.02	4.08
ADDER WT/IN	0.06	0.10	0.15	0.20	0.29

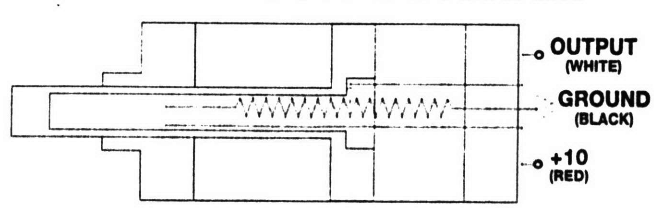
epair Parts

PART	DESCRIPTION
RPFC-Bore Stroke-Options	Replacement Cylinder
D-53129-Stroke	Replacement Probe

ow to Order

d the bore size, stroke and options needed to the basic
del number shown above for a replacement cylinder.
d the stroke length to the basic model number shown
ove for a replacement probe. For example, a replacement
be for a 6" stroke Position Feedback Cylinder would be
lered as a D-53129-6.

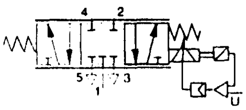
LRT CIRCUIT DIAGRAM



STROKE = 0; OUTPUT VOLTAGE = 0 VOLTS
STROKE = FULL; OUTPUT VOLTAGE = 10 VOLTS

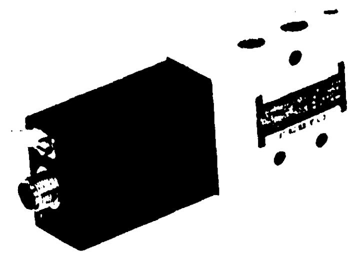
Appendix E – Festo fast-acting Proportional Valve Data Sheets

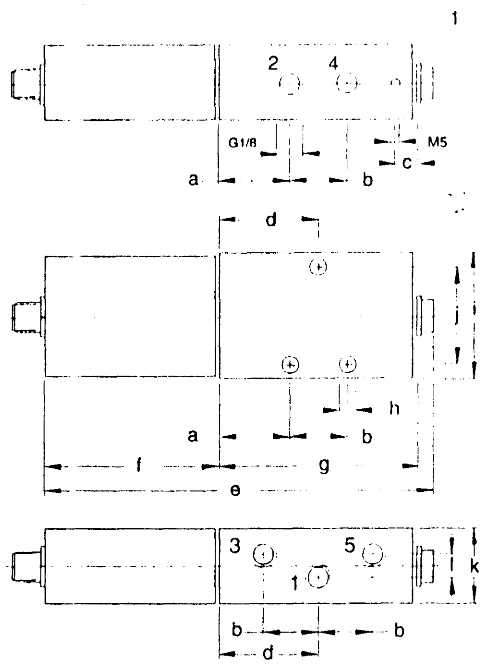
Servopneumatic Valve Type MPYE-5-1/8



The servopneumatic valve, type MPYE, regulates the flow of air to the cylinder in direct proportion to the analog electrical signal received from the axis controller.

The extremely fast, 5-ms response time and infinitely adjustable positioning capability make it ideal for very high cycle, pneumatic- cylinder positioning applications.





Accessories
Angle Socket,Type
12956 SIE - WD - TR
Straight Socket, type
18494 SIE - GD

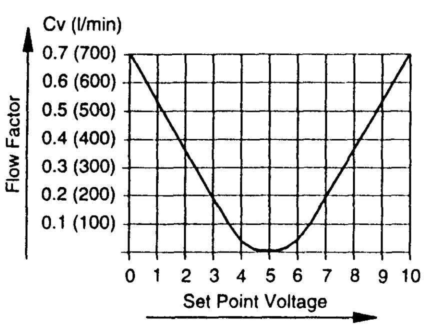
Dimensions

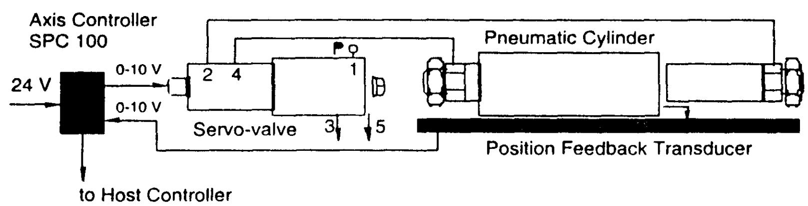
in / mm

a. 1.06 / 27
b. 0.75 / 19
c. 0.26 / 6.5
d. 1.44 / 36.5
e. 5.35 / 136
f. 2.36 / 60
g. 2.72 / 69
h. 0.22 / 5.5
i. 1.77 / 45
j. 1.38 / 35
k. 1.02 / 26
l. 0.28 / 7

1 relief port

Flow vs. Set Point Voltage





Part. No. / Type	30444 / MPYE-5-1/8
Medium	5 micron filtered,-unlubricated air (No condensation allowed)
Mounting	Easily mounted at any angle
Connection	G1/8 ISO
Orifice	0.24 in / 6 mm
Cv Factor	0.7 Cv / 700 l/min
Operating Voltage	24 VDC
Power Consumption	2 W (piston at mid-position), Max. 20 W
Duty Cycle	100%
Residual Ripple	10%
Control Voltage	0 to 10 volts d.c.
Input Resistance	5k - ohms
Frequency Response	100 Hz at 20 to 80% of valve stroke, P max.
Response Time	5 ms at 20-80% of valve stroke, P max.
Hysteresis	0.3% of control voltage
Linearity	1% of full range
Temperature	Medium = +41 to 104°F / +5 to 40°C' Ambient = +32 to 122°F / O +50°C
Materials	Housing; Anodized Al
Protection	IP 65
Weight	0.71 lb. / 0.32 kg.

Appendix F – C Program for Data Acquisition

```
//:     TESTING.CPP
//. Programs to take data from MEI motion control to be later displayed in MATLAB
//.     Written by Keith Breinlinger, Summer 1997
//.     Master's Thesis work: VirtuaRide Project

//*************************************************************************************

#include <stdio.h>
#include <stdlib.h>
#include <dos.h>
#include <conio.h>
//#define PCDSP_LIB
#define PCDSP_LIB
#include "pcdsp.h"
#include "extras.h"

//*************************************************************************************

#define AXIS        0
#define CONV                228
#define DAC_COM             6
#define DAC_ACT             7

        double position0;
        double position1;
        double accel;
        double decel;
        double velocity;
        double jerk;
        double sample =0;

//****************************Function Prototypes*****************************************
double input_accel();
//double input_decel();
double input_velocity();
double input_jerk();
double input_position(int choice);
void error(int error_code);
//int controls();
//int change_values();


//-----------------------------------------------------------------------------------------
char user_input()
{
```

```
printf("\t\t  MOTION DATA AQUISTION PROGRAM\n\n");


if (sample > 20 || sample <= 0)
{
        printf("Enter desired sample time (in secs) Max 20 secs.");
        scanf("%2d", &sample);
}

int motion =0;
if (motion > 5 || motion >= 5)
{
        printf("Enter the number corresponding to the motion profile desired."
                        "\n\t(1) S-curve motion"
                        "\n\t(2) Parabolic motion"
                        "\n\t(3) Trapezoidal motion"
                        "\n\t(4) Step input\n");
        motion = getch();
}

switch(motion)
        {
                position0 = (input_position(0))*CONV;
                position1 = (input_position(1))*CONV;
                case '1':
                case '2':
                        accel = (input_accel())*CONV;
                        //decel = (input_decel())*CONV;
                        velocity = (input_velocity())*CONV;
                        jerk = (input_jerk())*CONV;
                        break;
                case '3':
                        accel = (input_accel())*CONV;
                        //decel = (input_decel())*CONV;
                        velocity = (input_velocity())*CONV;
                        break;
                case '4':
                        accel = 32768;              //max value for trapezoid profile
                        //decel = 32768;             //max value for trapezoid profile
                        velocity = 32768;    //max value   for trapezoid profile
                        break;
        }
        return motion;

}
```

```
//92-------------------------------------------------------------------------------------
double input_accel()
{

        printf("Enter desired acceleration in inches/sec^2\n");
        double accel;
        scanf("%lf", &accel);
        return accel;
}

//---------------------------------------------------------------------------------------
double input_decel()
{

        printf("Enter desired decceleration in inches/sec^2\n");
        double decel;
        scanf("%lf", &decel);
        return decel;
}

//---------------------------------------------------------------------------------------
double input_velocity()
{

        printf("Enter desired maximum velocity in inches/sec\n");
        double vel;
        scanf("%lf", &vel);
        return vel;
}

//---------------------------------------------------------------------------------------
double input_jerk()
{

        printf("Enter desired jerk in inches/sec^3\n");
        double jerk;
        scanf("%lf", &jerk);
        return jerk;
}

//132------------------------------------------------------------------------------------
double input_position(int choice)
{

        printf("Enter desired position to move to in inches\n");
```

```
	printf("Standard position move is from 1 inch to 13 inches <Hit enter to keep
values>\n");
	double pos=-1.231129812;  //An odd number no one will ever enter...
	if (choice)
		{
		printf("Enter desired position to move to. (in inches)\n");
		scanf("%lf", &pos);
		if (pos=-1.231129812) pos==13;
		}
	else
		{
		printf("Enter desired position to move from. (in inches)\n");
		scanf("%lf", &pos);
		if (pos=-1.231129812) pos==1;
		}
	return pos;
}

//154-------------------------------------------------------------------------------
void error(int error_code)
{

	char buffer[MAX_ERROR_LEN];

	switch(error_code)
	{
	case DSP_OK:
		break; //No errors

	default:
		error_msg(error_code, buffer);
		fprintf(stderr, "ERROR: %s(%d).\n", buffer, error_code);
		exit(1);
		break;
	}
}

//173-------------------------------------------------------------------------------

int main()
{

	unsigned int i;
	int error_code;
	size_t buffer_length;
```

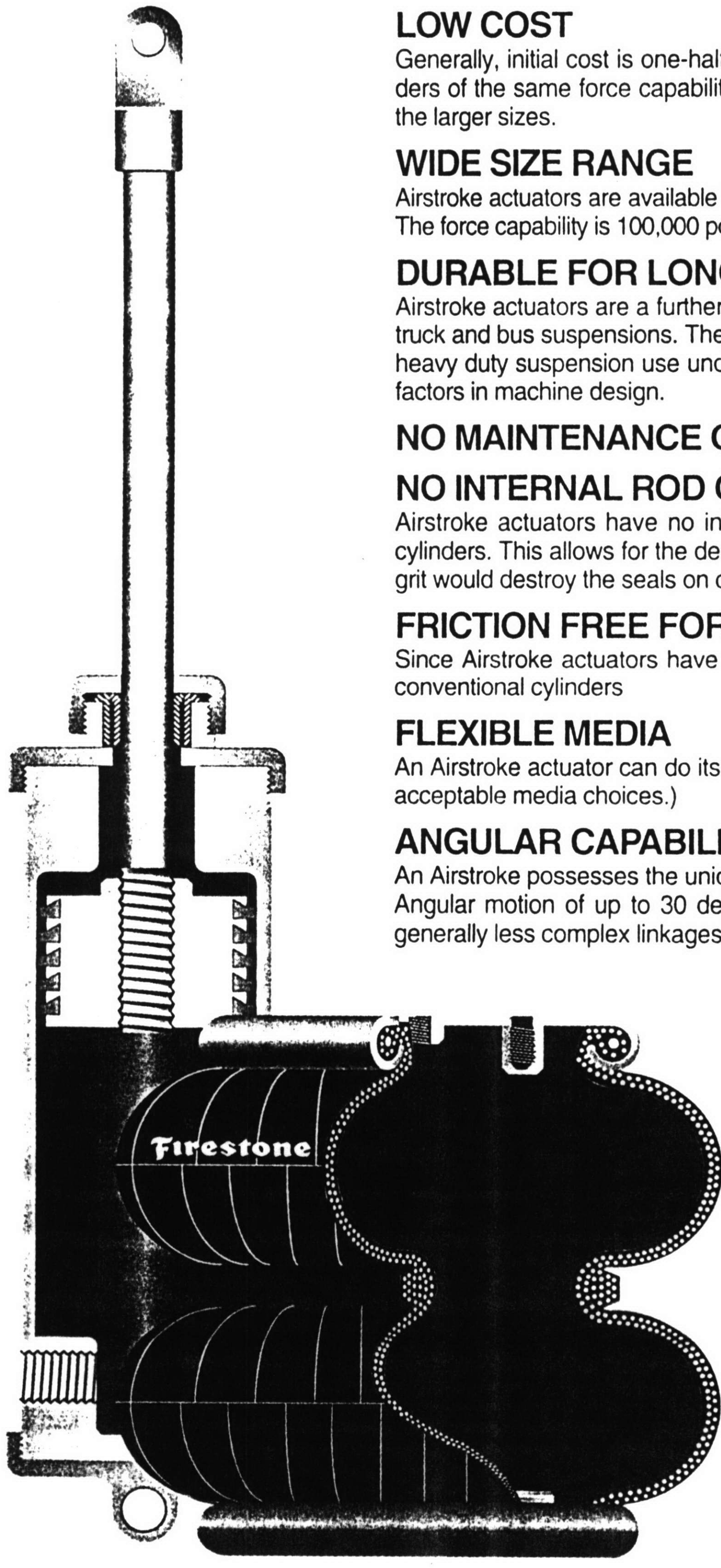
```
long
        *apos,
        *cpos;

int
        *time,
        *state,
        *voltage;

int
        pos_error[400];

if (dsp_init(PCDSP_BASE))        //Any problems initializing?
        return dsp_error;        //If so, quit and return MEI error code.

error_code=do_dsp();
error(error_code);
error(dsp_reset());
error(set_sample_rate(2250));


set_feedback(AXIS, 1); //Sets axis for analog feedback control.

char motion=user_input();  //Asks user for accel, vel ,jerk and position of move
//error(controls());              //Asks user for PID and FF parameters


s_move(AXIS,position0,300,500,700);    //Slow s-curve move to position
set_position(AXIS, (position0));  //Move to start position

while (!axis_done(AXIS))
        printf("Setting command and actual to start position\n");

link(AXIS,DAC_COM,1.0,LINK_COMMAND);
link(AXIS, DAC_ACT,1.0,LINK_ACTUAL);

buffer_length== sample * dsp_sample_rate();
printf("Buffer length is:%d\n", buffer_length);


        apos== calloc(buffer_length, sizeof(apos[0]));
        cpos== calloc(buffer_length, sizeof(apos[0]));
        time== calloc(buffer_length, sizeof(apos[0]));
        state== calloc(buffer_length, sizeof(apos[0]));
        voltage== calloc(buffer_length, sizeof(apos[0]));
```

```
		if(!(apos && cpos && time && state && voltage))
		{	fprintf(stderr, "Not enough memory.\n");
			return 1;

		}

		fprintf(stderr, "Press any key to begin.\n");
		getch();

		fprintf(stderr,"Sampling...\n");

//238
	switch(motion)
		{
			case '1':  //S curve motion
				start_s_move(AXIS,position1,velocity,accel,jerk);
				break;

			case '2':  //Parabolic curve motion
				start_p_move(AXIS,position1,velocity,accel,jerk);
				break;

			case '3':	//Trapezoidal motion
			case '4':	//Pseudo-step motion (Max values used for trapezoidal
motion)
				start_move(AXIS,position1,velocity,accel);
				break;

		}
//255
	get_tuner_data(AXIS,buffer_length,apos,cpos,time,state,voltage);
	fprintf(stderr,"Done.\n");
	//printf("time\tapos\tcpos\tstate\tvoltage\terror\n");
	for (i=0; i < buffer_length; i++)
	{
		pos_error[i]=cpos[i]-apos[i];
		printf("%u\t%ld\t%d\t%d\t%d\t\n",
			time[i], apos[i], cpos[i], state[i], voltage[i], pos_error[i]);
	}

	printf("\tFinished sampling data...");
	set_command(AXIS,0);
	return 0;

}
```

```
//272-----------------------------------------------------------------------------------------
/*int controls()

int filter[10];

//get_filter(AXIS, filter);
printf("\n\tThe current settings are:"
        "\n\t\t0)Proportional gain = %d"
        "\n\t\t1)Deravitive gain = %d"
        "\n\t\t2)Integral gain = %d"
        "\n\t\t3)Acceleration feed forward = %d"
        "\n\t\t4)Velocity feed forward = %d"
        "\n\t\t5)Integration summing limit = %d"
        "\n\t\t6)Voltage offset = %d"
        "\n\t\t7)Voltage output limit = %d"
        "\n\t\t8)2^n divisor magnitude shift = %d"
        "\n\t\t9)Friction feed forward = %d",
            DF_P, DF_D, DF_I, DF_ACCEL_FF, DF_VEL_FF, DF_I_LIMIT,
DF_OFFSET,
            DF_DAC_LIMIT, DF_SHIFT, DF_FRICT_FF);

printf("/n/t DO YOU WISH TO CHANGE ANY OF THESE VALUES?(Y/N)\n");
char key = getch();
if key==("y" || "Y")
    change_values();

return (set_filter(AXIS, filter));


//-----------------------------------------------------------------------------------------
int change_values()

int newvalue;

    printf("Enter the number you wish to change.\n")
    char key2 = getch();
    switch(key2)
    {
    case '0':
        printf("Enter new proportional gain value"\n);



        scanf(%d, &newvalue);
        [
```

```
	Coefficents[DF_P]= 1000;			//Set proprtional gain
	Coefficents[DF_D]= 200;				//Set derivative gain
	Coefficents[DF_I]= 0;				//Set integral gain
	//Coefficents[DF_ACCEL_FF]= 0;		//Set acceleration feed forward
	//Coefficents[DF_VEL_FF]= 0;			//Set velocity feed forward
	//Coefficents[DF_I_LIMIT]= 0;			//Set integration summing limit
	//Coefficents[DF_OFFSET]= 0;			//Set voltage output offset
	//Coefficents[DF_DAC_LIMIT]= 32000;	//Set voltage output limit
	//Coefficents[DF_SHIFT]= 0;			//Set 2^(n) divisor *Gains divided by
2^n
	//Coefficents[DF_FRICT_FF]= 0;		//Set friction feed forward



return dsp_error;


*/




//*******************************************************************************************
```

Appendix G – Firestone Airstroke Actuator Data Sheets



LOW COST
Generally, initial cost is one-half or less than conventional pneumatic or hydraulic cylinders of the same force capabilities. This initial cost advantage is many times greater in the larger sizes.

WIDE SIZE RANGE
Airstroke actuators are available in sizes ranging from 3.4 inches to 37 inches in diameter. The force capability is 100,000 pounds. Strokes of up to 14 inches are possible.

DURABLE FOR LONG LIFE
Airstroke actuators are a further application of Firestone's time proven Airide springs for truck and bus suspensions. The long life and durability necessary for millions of miles of heavy duty suspension use under adverse environmental conditions are also important factors in machine design.

NO MAINTENANCE OR LUBRICATION REQUIRED

NO INTERNAL ROD OR PISTON
Airstroke actuators have no internal rod, piston, or sliding seals as do conventional cylinders. This allows for the design of Airstroke actuators into applications where dirt or grit would destroy the seals on conventional cylinders.

FRICTION FREE FOR IMMEDIATE RESPONSE
Since Airstroke actuators have no sliding seals, there is no breakaway friction as with conventional cylinders

FLEXIBLE MEDIA
An Airstroke actuator can do its work with either a liquid or gas (Please see page 14 for acceptable media choices.)

ANGULAR CAPABILITY
An Airstroke possesses the unique capability of stroking through an arc without a clevis. Angular motion of up to 30 degrees is possible, along with the design advantage of generally less complex linkages.

SIDE LOADING CAPABILITY
Airstroke actuators, within certain limits, are not affected by side loads as are conventional cylinders. This misalignment capability eliminates potential rod bending, scoring, and excessive seal wear common to conventional cylinders.

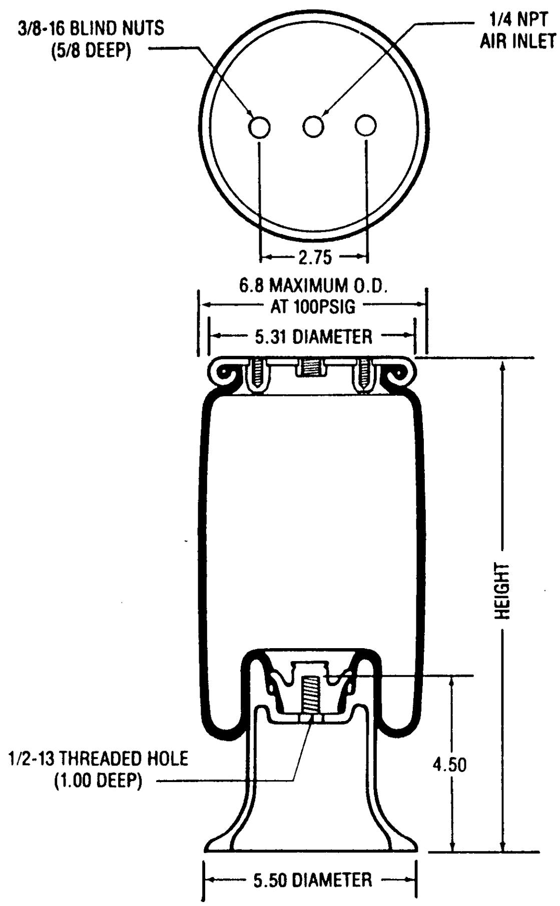
COMPACT STARTING HEIGHT
Airstroke actuators have a low profile compared to conventional cylinders. Our smallest Airstroke actuator (3.4 inch/dia.) collapses to just 1.5 inches in height, while our largest triple convoluted Airstroke (37 inch/dia.) will collapse to a very compact 5.5 inches.

FACTORY SEALED AND TESTED
Most Airstroke actuators feature Firestone's proven concept of crimped end plates. The crimped design allows for preshipment testing and quicker installation on equipment.

PLEASE REFER TO PAGE 15 FOR A THOROUGH DISCUSSION OF ACTUATION.

1T26D-7 Firestone Airstroke® actuators · Airmount® isolators

	Description	Order No.
Style 1T26D-7 Two Ply Bellows	Blind nuts, 1/4 NPT	WO1-358-9327
Assembly weight .... 6.0 lbs.		

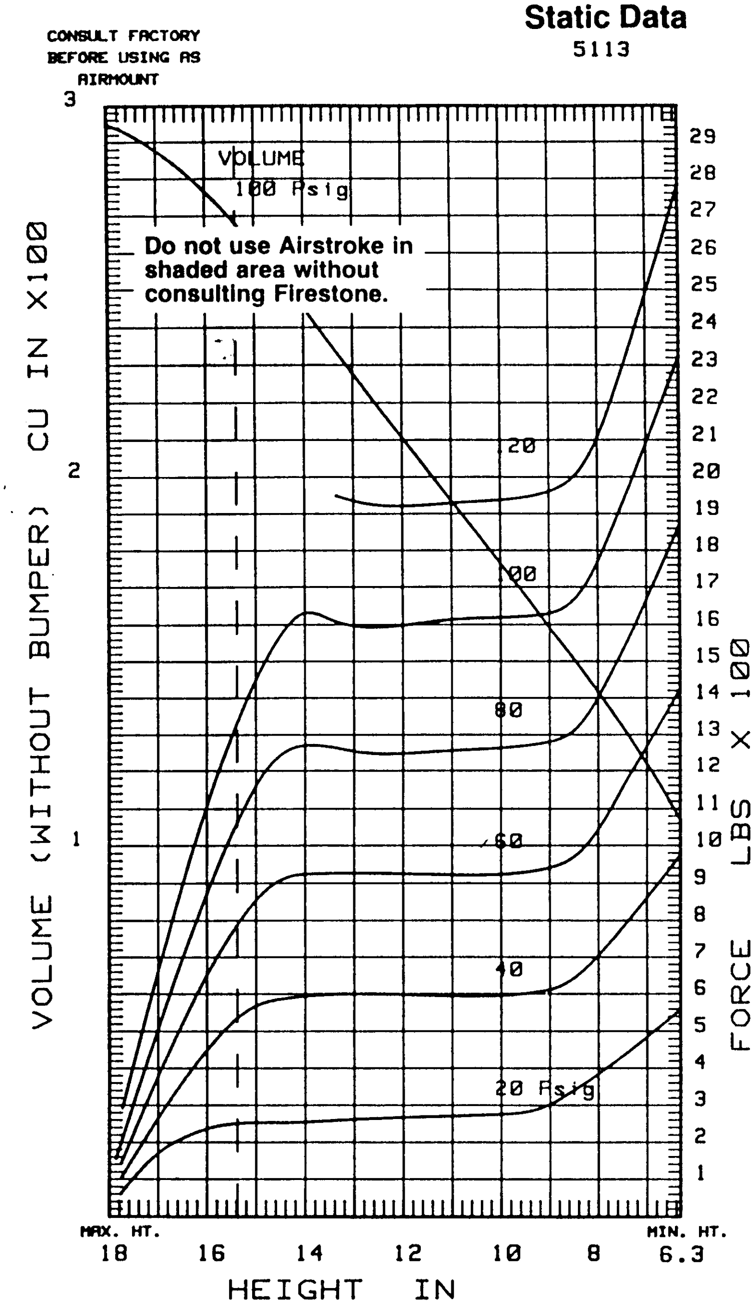


NOTE: Bellows will not compress properly with less than 10 PSIG internal pressure.

NOTE: This part is also available with an upper bead ring (rather than end plate.) SEE PAGE 9.

Static Data

5113



SEE PAGE 12 for instructions on how to use chart.

Dynamic Characteristics at 13.0 in. Design Height (Required for Airmount isolator design only)				
Volume @100 PSIG = 228 in³			Natural Frequency	
Gage Pressure (PSIG)	Load (lbs.)	Spring Rate (lbs./in.)	CPM	HZ
40	600	87	71	1.19
60	930	120	67	1.12
80	1,250	141	63	1.05
100	1,590	184	64	1.06

Force Table (Use for Airstroke actuator design)

Assembly Height (in.)	Volume @ 100 PSIG (in³)	Pounds Force @ 20 PSIG	@ 40 PSIG	@ 60 PSIG	@ 80 PSIG	@ 100 PSIG
15.0	263	250	570	850	1,160	1,450
13.0	**228**	**260**	**600**	**930**	**1,250**	**1,590**
11.0	194	270	600	920	1,260	1,610
9.0	**160**	**300**	**610**	**940**	**1,280**	**1,630**
7.0	122	480	860	1,270	1,660	2,090

Appendix H – MEI Motion Control PC-DSP 4 axis card

PCX/DSP specifications

Interface:

PC/XT/AT compatible
Switch-selectable base address, I/O mapped
Switch-selectable interrupts

Digital Sampling Rate:

16.0 kHz (1 axis)
4.0 kHz (4-axes simultaneously, maximum)
2.0 kHz (8-axes simultaneously, maximum)
1.25 kHz (default)
User programmable

Servo Output:

+/- 10 V DC @ 16-bit resolution (from 18-bit conversion)

Step Output:

Maximum Step Frequency: 375 kHz
50% Duty Cycle
Non-linearity < 1% at Full Scale

Ranges:

Position: 32-bit, +/- 2.15 billion counts (steps)
Velocity: 32-bit, 1/65,535 to 32,767 counts (steps) / sample interval
Acceleration : 32-bit, 1/65,535 to 32,767 counts (steps) / sample interval ^{2}

Position Feedback:

Input Frequency: 5 MHz (max)
Quadrature, single-ended or differential (A,B,I)
Digital Noise Filtering

Motion Profiles:

Trapezoidal, Parabolic, S-Curve acceleration & deceleration

Dedicated I/O:

TTL compatible, 4.0 mA drive on outputs
No pull-up resistors are included.

Dedicated Inputs (Per axis):

Forward Limit (POS)
Reverse Limit (NEG)
Home
Amp-Fault

Dedicated Outputs (Per axis):

In-Position
Amp-Enable

User I/O:

2/4 axis models - 44 lines
6/8 axis models - 24 lines
TTL compatible, 4.0 mA drive on outputs
Direct access from Host PC

Analog Inputs:

8 Channels @ 12-bit resolution
5V Unipolar input
+/- 2.5V Bipolar input
2.5 μsec conversion rate per channel
Direct access from Host CPU

Power Requirements:

		8 axis	*4 axis*
+5V	Icc =	.7 A max	.6A max
+12V	Icc =	8mA max	4mA max
- 12V	Icc =	18mA max	14mA max

Environmental Conditions:

0 - 60 degrees C   32 - 140 degrees F
20 - 95 % RH, non-condensing