The Mother of Invention

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This conference is about innovation and how it can arise from the use of simulation. As an interesting twist on this theme, I would like to describe to you why a new linear actuator had to be invented to solve an urgent requirement of the entertainment simulator business. I shall also describe some of the ways the actuator may be used in other industries.

"SIMULATORS"

Ask any non-technical person what a simulator is and the answer will be about teaching pilots to fly aircraft. Mention entertainment simulators and you will learn that the most important thing about them is that they move - to the general public a simulator is not a simulator unless it moves.

Entertainment simulators do not actually simulate anything. They are fantasy machines in which the laws of nature are modified so that the experience that the public pays to receive does not closely resemble any physical reality. Instead, the machine portrays reality as the common man would prefer it to be - at least for three exciting minutes. Entertainment simulators are a spin-off from military machines, as I shall explain.

The EW Simulator at Stanmore

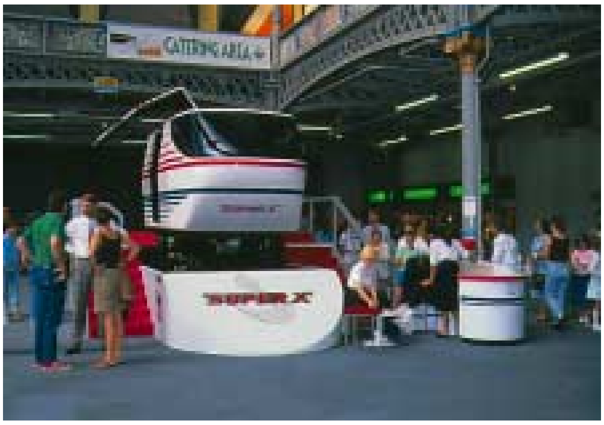
Twenty years ago I built a very large, complex and expensive simulator for Marconi at Stanmore which was designed to test various types of electronic warfare equipment. Electronic Warfare is a game of Hide and Seek, a sort of lightning-fast blindfold mobile three-dimensional chess game played between computers and microwave equipment at extremely high speed and without the real-time intervention of any human being. For example, radar systems and jamming equipment will try to outwit each other as an aircraft comes streaking in across enemy territory whilst the enemy tries to get a fix on the aircraft and fire off guns or missiles to knock it out of the sky. The jammer must win the EW battle if the aircraft is to survive. The electronic warfare simulator is designed to test to the limits in a real-time scenario the efficiency of several kinds of EW equipment hardware - and the skills of the programmers, who try to incorporate within the high-speed control software of the radar, the jammer or the missile-guidance system all the secret information and all the counter strategies from which the device must choose from instant to instant as the EW battle proceeds.

The problem is that everything happens very quickly, is very complex and quite invisible. It is incredibly difficult to follow the test sequence in real time, to understand what is happening, who is winning, who is losing, and to know where to look afterwards in the recorded data to find out why. I ask you to remember that the whole thing is, in any case, imaginary. It is a simulation, and it is designed to convince the software in the equipment under test that it is <u>not</u> sitting quietly in an anechoic chamber in a TEMPEST-rated building at Stanmore but it is, perhaps, fixed to an aircraft thousands of miles away, streaking in fifty feet above the ground at Mach 1 against a densely-defended target.

To improve matters I therefore decided that I would try to transform the microwave signal parameters into visible images which could be shown on a TV screen. In effect I decided to give the test engineers a view of the microwave world as it would be "seen", for example, by the microwave sensors in an attacking aircraft. I needed some very large computers for this work and I made my first encounter with Computer Generated Imagery.

I was astonished to discover how exciting this visual simulation was, for me and for the visiting VIPs and senior military personnel from many countries who watched the displays on the TV screens. Clearly, those normally dour and serious individuals were fascinated and found themselves caught up in what they saw. I resolved that I would find some way to allow the general public to experience that sort of excitement. So I left Marconi and set up a company which built its first "Super X" Venturer simulator in 1985.

What is an Entertainment Simulator?



Super X "Venturer" machine

A typical entertainment simulator consists of a small cinema in which a group of between twelve and forty people watch a projected television display and listen to a soundtrack, whilst the whole cinema moves on a hydraulic motion base. As I discovered later, the idea was first conceived by Douglas Trumbull, the special effects film producer, in 1978.

If you have watched a simulator working from the outside you will see that it weaves and dodges about through small angles of pitch and roll and it also bobs up and down a few inches, apparently in a random way. But I assure you that when you get <u>inside</u> the capsule the effect is quite extraordinary - and, without giving away too many secrets about how the trick is done, I can say that it is highly dependent upon the total exclusion of the external world.

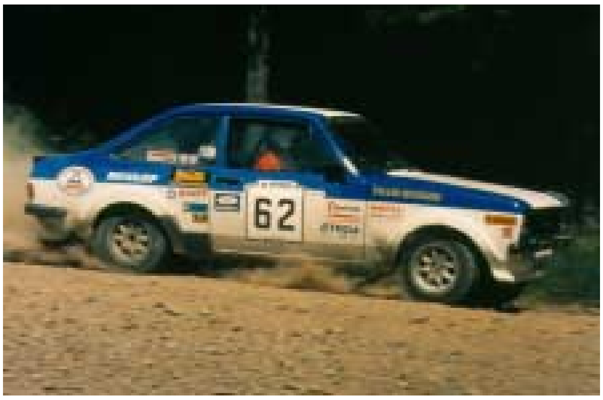
From then on it depends upon Einstein's first principle of General Relativity. This says that, in a closed environment, it is impossible to tell the difference between gravitational and inertial forces - in short, you do not know which way up you are if you get lots of other signals to your senses which tell you that "down" is not in the direction you thought it was.

Finally, motion simulation works because your body ignores a steady acceleration after the first fraction of a second. All these things taken together make it possible for a "motion simulation choreographer" to persuade the occupant of a capsule which only moves a few inches that he/she is swooping violently around the sky, racing around the Isle of Man on a motorbike, skiing in the Alps, rushing through a canyon on a raft, or sailing gracefully about in a microlight aircraft.

THE IMPORTANCE OF BODY MOTION.

Perhaps I should explain why a vehicle simulator has to have any motion system at all. It is important to understand that no one drives - or flies - in accordance with visual cues as the primary response. Careful studies show that a person engaged in vehicle guidance control responds first to tactile disturbance and only later to visual field disturbance. This is thought to be due to the experiences of early life which teach balancing skills as fast reactions to external forces on the body. These reactions are entirely subconscious and they act on the human brain to update the model of body motion and to predict its future position - there is no delay in an interposed, consciously-accessible reasoning process.

When we take control of a vehicle - for land, sea or air - we bring with us our fast reactions to body forces and we use them to measure our mastery of the vehicle. We deliberately learn how to blend with the vehicle - to feel that it is a natural extension of our body - and to get an instinctive understanding of where the edges of the vehicle are and what is happening to them. By using the controls to move the vehicle, we also gain an ability to predict the future position of the craft and when it is moving we learn how to interpret its interactions with the surrounding medium.



Driving by the seat of the pants

We say that a vehicle is under control when it "feels right" - when the driver is able to make the vehicle *feel* as he/she wishes, whether in response to input commands or against disturbances from the outside environment. The visual experience is not given the same level of importance in our assessment of our feelings of security in the vehicle. This is because what we feel is the complex of *accelerations*, which are integrated over time to produce velocities and further integrated to result in displacements. The displacements alter the visual field, but the changes are perceptible *later than the body* *sensations.* I am sure that many of us have had the electrifying experience of losing control of a car on an icy surface, even for a second. Visually nothing happens in that short time - the event is felt - and control can often be regained before a passenger knows anything about it.

I have quoted vehicle control as an example of how important sensations of force - of acceleration - are to us in our daily lives and how we use the instinctive responses of the human body to control machines. The most important aspect of this brain function is that *motion sensations go directly to the subconscious. There is no conscious thought between sensory input and trained or instinctive response.* All the appropriate body chemical responses are triggered.

The essence of simulation - of Virtual Reality - is that it should be a compelling fantasy. That is, during the progress of the simulation it must appear to be "real", even if you understand that it wasn't real *when you think about it afterwards*. If you have never ridden a good simulator then I can assure you that you will be very surprised just how compelling the experience can be. Thorough simulation is capable of disconnecting you thoroughly from the real world and immersing your mind within a Virtual World, in which the laws of physics can be different and in which you need not be limited to being the self that you are in your life outside the simulator.

As I have previously explained, many of the effects on you are induced subconsciously; they go directly to the part of your brain over which you have no immediate control. Even if you are intellectually aware of how the simulator is designed and how it is achieving these disturbing effects, it is very difficult to stand back and observe yourself objectively in such a situation. Your instincts make you concentrate on all the action in this virtual environment and get on with the interesting and exciting job of flying or driving the simulated vehicle and participating in the competitive event which is taking place, between you and the machine or between you and your friends in other "Virtual Vehicles". You will find that the stress which is placed on you by your natural urge to compete and even to "survive" does not make you want to get out of the simulation but actually to go further in. This effect has been observed for many years in professional training simulators.

Stress, <u>especially stress from motion cues</u>, increases the psychological "grip" of a simulation on the participant. *Entertainment simulators are very profitable machines, because motion is always involved in the most exciting entertainment experiences, and because motion cues have such a powerful and irresistible effect*

The problems of hydraulics

Until now, the only way to produce such precise and powerful motion cues for simulation has been by using hydraulics. Electric motors driving screw-jacks can be "beefed-up" to produce a large thrust but they cannot be designed to have also the extreme sensitivity and the fast response which is vital to the simulation illusion. A good motion system must be equally capable of producing (say) the strong sensations of "cornering" in a vehicle as in providing the differences in road feel from gravel or tarmac or grass. Hitherto, only hydraulic rams have been able to do this, at great expense and complication and with the inevitable oil leaks and fine oil spray onto the surroundings. When the simulator is used indoors, the damage to nearby fabrics, the fire hazard and the possible toxic effects of the oil mist create major problems.

Further, hydraulic motion systems waste a lot of energy. Whenever a hydraulic ram is moved, oil at high pressure is transferred from the power unit into the system and an identical volume of oil, at zero pressure, returns to the tank. 98% of the energy disappears as frictional heat when the oil passes through the various control valves.

THE NEED FOR INVENTION

There is a very large market for small simulators indoors, in arcades and family entertainment centres and in portable trainers for military and civilian personnel. Hydraulic motion systems cannot be used for such machines, because the actuators demand so much power and because they mess-up their surroundings. A completely new technology has had to be invented to solve the problem.

A gas spring suspension

Suppose that we replace the hydraulic rams by pneumatic rams and we fill the space beneath the pistons with gas at a pressure sufficient to support the dead-weight of the capsule. Then we connect the pressurised part of the pneumatic ram to a small reservoir (a few litres) so that it forms a low-rate gas spring. The gas springs remove from the actuators the requirement to support the deadload and they act as reservoirs in which energy may be stored and from which it can be extracted later. There is no hydraulic oil, so there are no problems of oil friction losses, leaks or atomised sprays.

The actuator rams now only need to provide impulsive forces. There is no requirement for a steady upthrust. Power is only consumed when the simulator is in motion and the only power required is that necessary to change the kinetic energy of motion and to overcome any frictional losses. The power required is therefore a small fraction of that for a "hard" motion base.

A new type of linear electromagnetic actuator.

Since the forces must be coupled to a floating mass the actuators *have to be electromagnetic*. There is no other way to take a firm grip on a freely-suspended inertial object! Because no suitable electromagnetic rams were available to us in 1991, we had to develop a new type of actuator, which now turns out to have many other industrial applications.

What we have done, in concept, is to slice a rotary electric motor down to the middle, roll it out flat and then roll it back up again by taking the long edges of the strip and bringing them round to form a cylinder. We do the same with the armature and we put the armature shaft down through the centre of the cylinder to make a piston. What we now have looks just like a pneumatic or hydraulic ram. We call it a PemRam.

Prototype PemRam under test in 1993

For a motion base designer, one of the most interesting features of the product is that there is a direct electrical connection between the computer and the piston. The electric current itself provides the force and the acceleration of the ram is a direct function of that current. Acceleration is what the occupant of the simulator actually feels. Because there are no transport lags or fluid inertia, the system is inherently of wide bandwidth, able to respond as rapidly as it is possible to change the current in the coil inductance. It is therefore possible to produce motion cues that are exactly timed and precisely controlled.

PemRam motion bases consume only a few hundred watts in place of the several kilowatts required for even a small hydraulic motion system. They can be used for cinema-seat simulator mechanisms, for low-cost personal training simulators, and for small entertainment machines.

Lotus-designed ram in 1994

The electromagnetic ram as a force-measuring device

A few years ago I visited Simultronix in Los Angeles and for the first time I rode a motorcycle simulator that was fitted with pressure pads as part of a servosystem that allowed the rider to throw the machine about by changing his body position whilst being subjected to the appropriate visual, haptic and audible motion cues.

Although the prototype was not perfect the experience was mind-blowing. For the first time I felt totally in control of - physically at one with - a machine which I knew to be just steel and hydraulics but which *seemed to understand what I wanted it to do before I even thought about it.* Of course, this was because my own body movements had been instinctive and the sensors on the motorcycle simulator had always moved the hydraulics in response before I had begun to realise what was happening.

So I thought that if I could devise a technology to make body movement interaction generally available, Virtual Reality would become powerfully convincing and much more than just a visual experience. Some of the most exciting and enjoyable things that we do have a strong element of body movement control in them - and they are some of the most difficult and dangerous to learn. They are large markets for training simulation that involve body motion.

For example:-

Skiing, ski-boarding, ski jumping, skidoo racing .

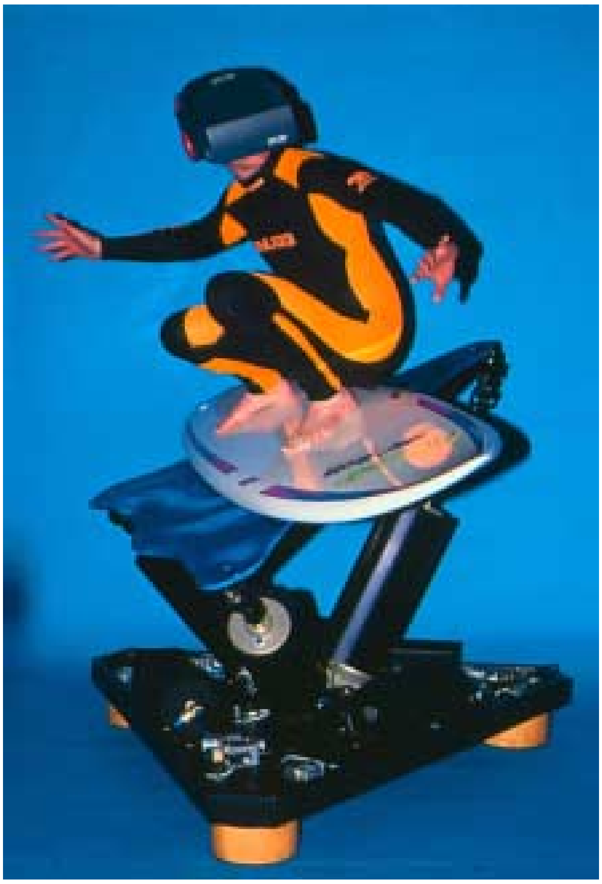
Ice skating, roller skating, skateboarding.
Surfing, wind surfing, sail-boarding, jet ski racing, water skiing.
Sailing, yachting, white-water canoeing.
Tobogganing, Bobsleigh racing, Motorcycle racing, Horse riding, Hang gliding

The air-sprung electromagnetic motion base is a force-balance system. The force generated by each ram is continually controlled to be exactly that which is needed to hold the desired position of the simulator - no more and no less. The current in an electromagnetic ram is therefore a direct measure of the load on it, having taken the gas spring pressure into account. This is in complete contrast to a hydraulic or an electric screw-jack system, both of which are "hard" and insensitive to changes in load upon them.

So when a human occupant of a simulator on an electromagnetic motion base moves or leans to left or right, fore or aft, the currents flowing in the rams will immediately adjust themselves to the degree necessary to compensate for the shift in the centre of mass, holding the position of the motion base constant. Thus by monitoring the relative values of the currents flowing in the rams, it is possible to know the position of the c.o.g. of the moving platform - that is, to sense any movements of the human occupant(s). The movements can then be fed back into the control computer to modify the progress of the simulation.

To illustrate the concept of body motion control we arranged for a local champion surfer to pose with a VR helmet on a motion base, and we later proved the principle in a complete working machine that was demonstrated on "Tomorrow's World". The technology now makes it possible for VR designers to create a whole new range of exciting, intimately-interactive Virtual Motion experiences***.***

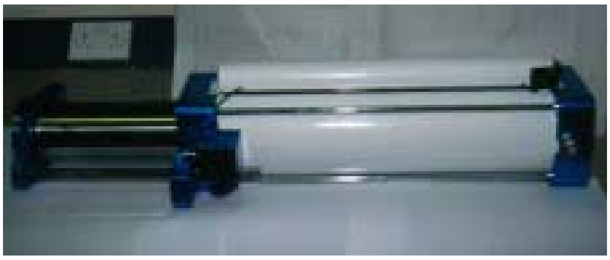
"The Cybersurfer" photograph became the logo of the electromagnetic ram in the VR industry.



The "Cybersurfer" concept

INDUSTRIAL APPLICATIONS

The publicity that resulted from the entertainment demonstrations of the ram soon led to a surprising variety of enquiries from engineers working in other industries. The PemRam was therefore redesigned mechanically and its electromagnetic systems were reconfigured to meet the demands of industry. It is now generally called a "ServoRam", since it is electrically equivalent to a three-phase AC servomotor. It is possible to construct rams of this design that have peak thrusts from 10 Newtons to at least 20,000 KiloNewtons.



Three-phase AC ServoRam

The industrial rams have several advantages:-

No stray fields. The "piston-in-cylinder" topology means that all the fields are contained within the ram, so that there are no spurious effects on its surroundings and no problems with swarf or steel grit.

Cleanliness. Modern versions of the ram are fully sealed. They will operate under water, in a vacuum or in a sterile atmosphere.

Silence. Most other types of electric linear actuator are noisy and the noise level increases with thrust rating and with wear. This can be a problem in machinery that operates continuously and in close proximity to a human being. It is especially distracting in a clean, high-technology environment.

Simplicity and reliability. Nothing moves except the output element . Nothing wears except two bearings and one air seal.

Wide operating tolerances. There is no requirement for micron filtration or white-glove maintenance.

High peak-to-mean thrust ratio. There is no hard limit to the transient peak thrust capability of the ram over a short time interval.

Speed of response. This is an order of magnitude better than the best hydraulic device.

Power regeneration. Using the ram in reverse mode, the machine operates as a generator - a controllable damper with an electrical power output that may be returned to the supply system.

Ease of control. Thrust is strictly a linear function of drive current, which may be made the controlled parameter and which is independent of the position of the piston. There is zero time delay between current flow and output thrust.

Precision. Zero backlash, zero transport lag and a wide control bandwidth lead to extreme precision, which is limited only by that of the position transducer. A precision better than one micron can be achieved.

Dual Action. Very significant amounts of power can be saved by using the pneumatic function of the ram to handle the static or quasi-static loads and the very fast electromagnetic function to manage precise positioning.

Auto-tuned spring function. Similarly, it is possible to combine a gas-spring technology with the electromagnetic forces to save power and to increase the operating speed of precision reciprocating machinery.

Scaling. The topology is scaleable over a wide range of thrusts and stroke lengths, using off-the-shelf components.

EXAMPLES OF INDUSTRIAL APPLICATIONS

Passenger Lifts. Many passenger lifts in buildings up to five storeys high are raised by hydraulic rams. Electromagnetic rams, several metres long, can replace them with an efficient, silent, clean and much more reliable product - that might eventually be made for a price low enough for lifts to be fitted as standard in general private housing.

Automobile Suspensions. Several makers of luxury cars are considering the use of electromagnetic suspension systems. It is rather too early in its development for the device to function well as a power element in active suspensions but, acting as a damper, can vary its characteristics under computer control in milliseconds if required. That is, an electromagnetic suspension system can be instantly tuned for every road condition as it is encountered. What is more the energy absorbed by the damper (sometimes 300 Watts a wheel) is not thrown away as heat but can be fed back into the battery supply, saving fuel. Simultaneously, the fluid piston element can act as part of a self-levelling, height-adjusting fluid spring system.

Rail Coach Suspensions. Mathematical studies carried out by Loughborough University as part of an EEC programme show that the ideal suspension for a rail vehicle is an electromagnetic one. Parallel studies in association with two major European companies show that the necessary forces, displacements and power levels are now within the reach of the ServoRam technology.

Industrial Automation. The advantages of cleanliness, silence, high peak thrust, unlimited speed, intrinsic force-sensing, reliability and wide control bandwidth mean that the device has many factory applications. For example, the rams can replace hydraulics in food and drug manufacture, where contamination would be very expensive. In high-speed machinery such as that for sorting, transferring and packing goods, the unique ability of the electromagnetic actuator to "freewheel" when handling inertial loads saves a great deal of energy.

Doors and Vents. Although vent actuators only operate at infrequent intervals and their first cost must be low, they are often placed in almost inaccessible positions, so maintenance is very expensive and reliability is vital. The ServoRam is interesting because it has only one moving part - the piston itself.

Security. The power needed to operate a ServoRam can be stored in a small space - for a year or so in a battery or for several minutes in a charged capacitor. This means that the device can be self-contained, so that it may be used to carry out a security action in a no-power emergency. It would be possible for the device to drive a bullet-proof security screen into position faster than a robber could pull the trigger of a gun.

Stabilised Platforms. When optical devices like cameras or measuring equipment have to be mobile on a land or sea surface they need to be isolated from disturbances when they are in use. This is also true for guns, radar antennae and missile launchers. Previously, most stabilising arrangements have used “hard” mechanisms with powerful motors, gears and cranks to generate the movements that are necessary. There is considerable interest in using a gas-spring suspension to decouple the stabilised platform from external disturbances and to superimpose electromagnetic forces to hold a precise position.

Cross-country vehicle seating. Human beings need stabilisation to avoid fatigue and injury when driving vehicles such as earth-moving equipment across rough terrain for long periods. Although soft spring suspensions have already been tried, it is clear that a significant improvement would result from the use of electromagnetic actuators that combine an air-spring and an active position-stabilising function.

Pile Driving. As a result of earlier studies by a British architectural consultant, it seems to be feasible to use both the fast rise-time and the force-sensing feedback properties of the new ram in a novel form of high-speed pile-driver. This works by applying a powerful impulsive waveform to the pile at a frequency that adapts automatically to the characteristics of the soil and makes it more fluid.

Bulldozing, Planing and Ploughing. In the same way, it seems to be possible to reduce the mechanical forces used in earth-moving equipment of various kinds.

SUMMARY

From the very beginnings of the entertainment simulator business there has been a strong demand for something better than hydraulic rams to power the motion systems. Hydraulic mechanisms cause a variety of health and safety problems indoors and close to the general public and the technology was an obstacle to the rapid expansion of the market for small entertainment simulators.

We have been forced to develop a special type of dual-action pneumatic and electromagnetic ram to solve that problem. The rams were found to have many other useful features.

The demands of manufacturing industry have now encouraged us to extend the technology and to develop high-quality dual-action electromagnetic rams that are very precise and energy-efficient. The machines are directly compatible with factory automation standards and they are finding a variety of applications world-wide.