Development of a 5 axis upper limb force display operating in a VR environment for training

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Abstract

A 5 axis upper limb force display has been prototyped, the force display is operated in a virtual environment. The virtual environment is provided via a head mounted display (HMD). Specific applications demonstrating the prototype include opening a screw-type hatch and ten pin bowling. The head mounted display provides appropriate 3D images and sounds as they relate to the operators position, direction and situation, while the 5 axis force display dynamically reflects the operator's situation by simulating the virtual object's parameters in terms of force positive or negative in all 5 axes simultaneously. This paper provides an overview of the prototyped system's mechanics, functionality and effectiveness in terms of operation in the virtual environment.

Key Words: force display, training environment, virtual reality, virtual bowling

1. Introduction

This paper builds on the previous works of Takeda and Tsutsui "Development of a Virtual Training Environment" [1] and "On the Computer Simulation of Ball Dribble in the Virtual Environment" [2] which focused on the design, construction and application of a 2~3 axis force display capable of matching the human shoulder and elbow in terms of degrees of movement and strength. However this paper looks at the addition of rotation of the forearm controlled by an AC servo motor, as is the shoulder's rotary movement. Also the addition of wrist movement which is controlled by two pneumatic cylinders which contrasts with the usage to date of pneumatically controlled rubber actuators (RUB). This paper focuses particularly on the application of the constructed 5 axis force display to the simulation of VR ten pin bowling as a case study which fully demonstrates it's functionality in a virtual environment.

2. The force display

The addition of forearm rotation and flexing of the wrist have been added to the previous force display. The resultant prototyped 5 axis force display is shown in figure 1. The operator aligns their upper arm with guide 2, places their forearm in the cylindrical guide 1 and grips the handgrip as illustrated on the left hand side of figure 6. Figure 2 illustrates the force display's axes in relation to the operator as well as indicating the range of operation of each axis.

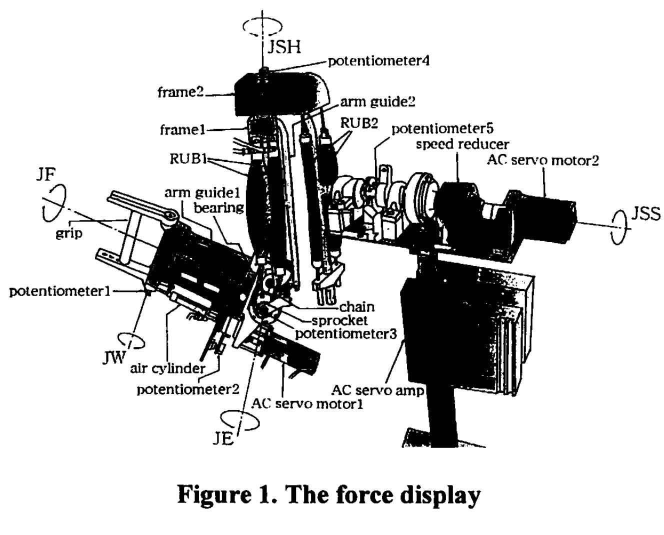


Figure 1. The force display

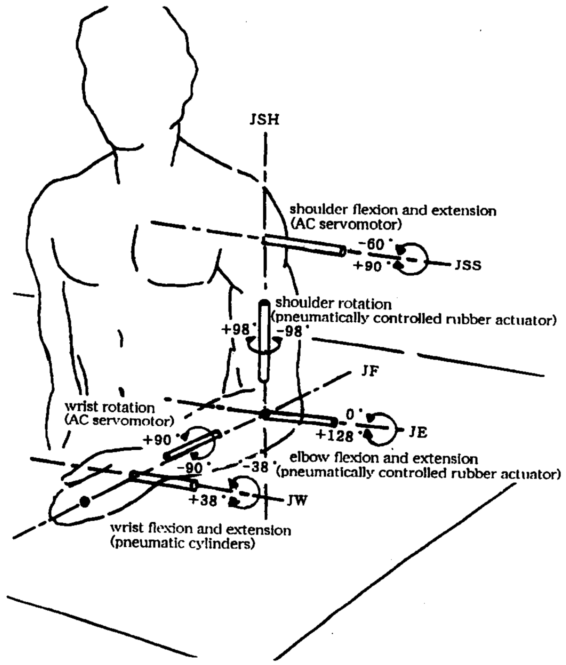


Figure 2. Operator - Force display axes positioning and range of operation

Table 1 details the characteristics of each axis, that is function, operating range (angle), mode of actuation, and maximum torque. Detail on the static and dynamic operating characteristics of the pneumatically controlled rubber actuators (RUB) is available from "Development of a Virtual Training Environment" [1], and has been thus omitted. Further the servo motor's forward and reverse operating current limits can be independently externally controlled. The servo motor's maximum rated armature excitation current occurs with an input of 2 volts.

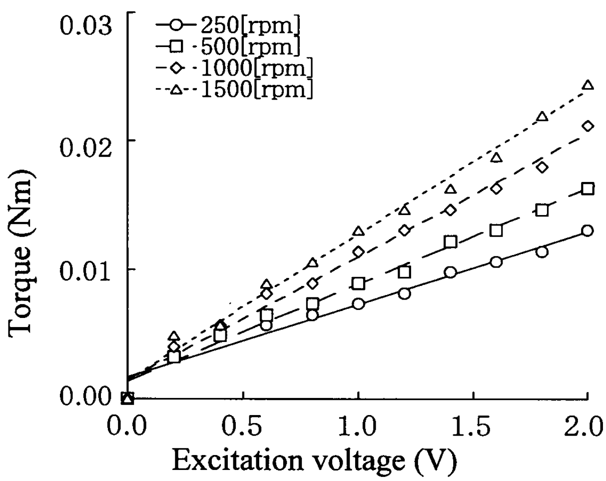


Figure 3. JF axis Torque characteristics

Figure 3 shows the torque characteristics varying with excitation voltage in the case of 4 set speeds of operation in the forward direction for the JF axis's servo motor, while figure 4 shows the same with respect to operation in the forward direction for the JSS axis's servo motor.

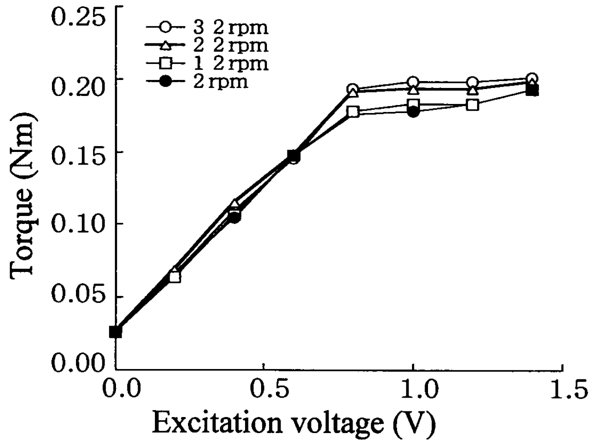


Figure 4. JSS axis Torque characteristics

Table 1 Force display specifications

Joint ID	Function	Range	Means of Actuation	Maximum Torque
JSS	shoulder extension	+90° -60°	AC servo motor	O.2Nm @32rpm
JSH	shoulder rotation	±98°	pneumatic rubber act.	50Nm @5kgf/cm^2
JE	elbow extension	+128°	pneumatic rubber act.	55Nm @5kgf/cm^2
JW	wrist flex	±38°	pneumatic cylinders	0.02Nm @5kgf/cm^2
JF	wrist rotation	±90°	AC servo motor	O.025Nm @1500rpm

Maximum torques were obtained by measuring the average maximum counter forces that could be exerted by a number of male University students in regard to each respective axis. For example in the case of the JF axis this was 0.03[Nm] and 0.3[Nm] in the JSS axis. These values thus provide the force display with the ability to compete on equal terms with the muscular ability of the operator should such functionality be required.

3. System level

The overall Virtual Reality (VR) system is shown in block diagram form in figure 6 while figure 5 depicts an operator using the VR system. The VR system consists of

3 main subsystems as follows: firstly provision of the visual aspect is via a Head Mounted Display (HMD) (40° field of vision), with a spatial and direction sensor (Fastrak - by the Polhemus Company) mounted on it. The visual I/O is handled by an Intergraph workstation. The VR graphical environment was created using 3D CAD (AutoCAD) and the World Tool Kit produced by the Sense Company. The auditory aspect of the system is provided by a sampler, effector, amplifier and headphones via a MIDI interface. Finally the above mentioned (Section 2) force display and it's respective actuators are controlled via a PC. The respective actuator's inputs controlling the torque and resultant change in output position sensors are handled via a PC's parallel I/O ports thus providing control of actuator position and velocity.

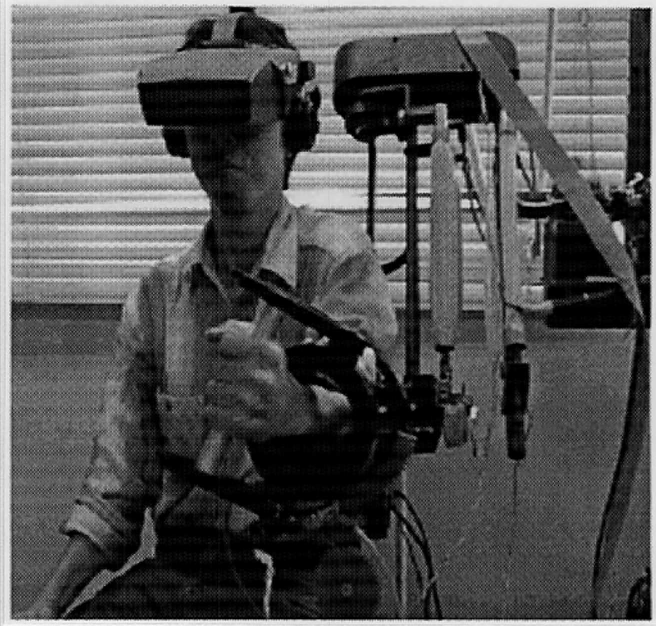


Figure 5. The Physical system

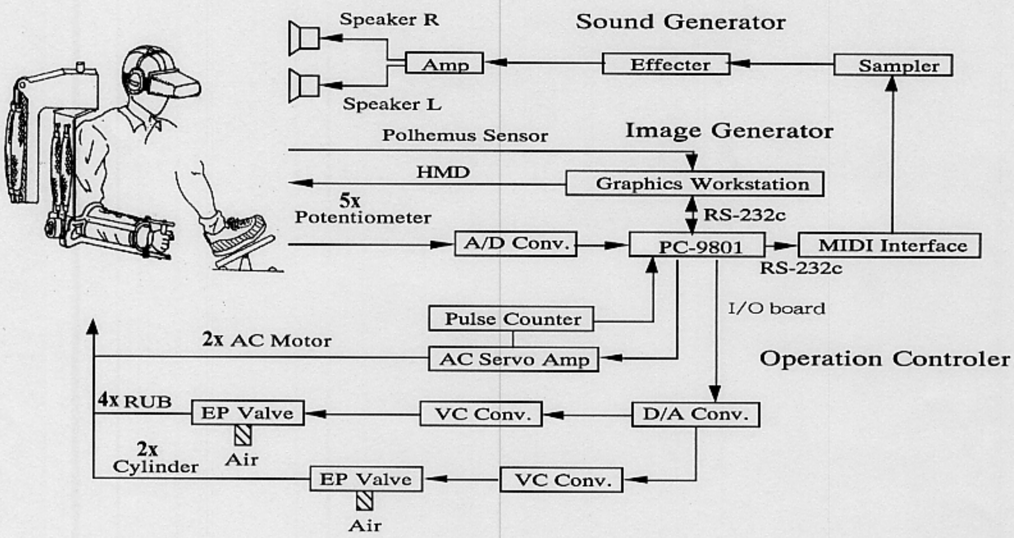


Figure 6. System schematic

4. The force display in the virtual environment

4.1 Opening and shutting a screw-type hatch

The first trail application to which the 5 axis force display was employed for was the simulation of opening a screw-type hatch.

The stages of operation were as follows:

1. firstly taking hold of the hatch's handle
2. turning the handle
3. turning the handle till free
4. and finally pushing the hatch open.

In terms of providing the necessary force feedback control to simulate the handle's operation the respective axis are JF for turning the handle and the JE and JSS axes for opening the hatch. Taking the operation step by step, firstly the moment the virtual hand is registered as taking a hold of the handle the JF axis servomotor stops, the potentiometer on the JW axis senses the wrist's movement while the JW pneumatic cylinders follow the action. The handle is a right hand screw thus opening clockwise and closing anti clockwise. As the handle is loosened the torque loading reduces proportionally until the handle is free, thus imparting a sense of realistic force feedback in this respect.

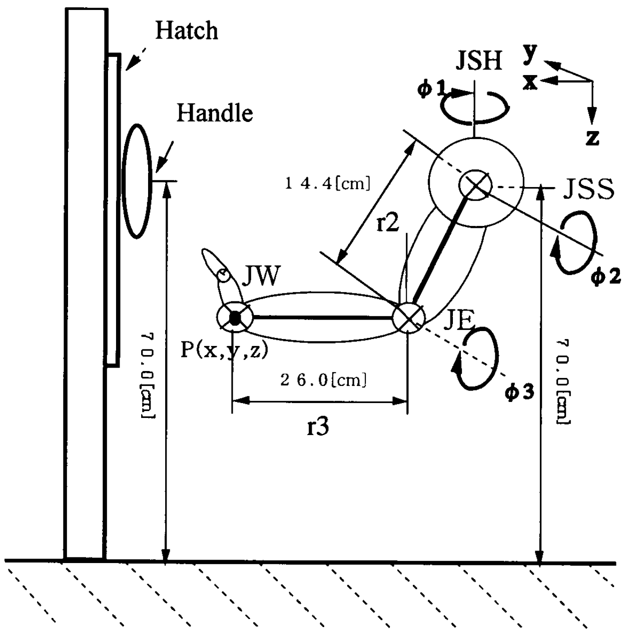


Figure 7. Arm co-ordinates in the virtual environment

The wrist's position shown in Figure 7 is given by

$$x=\left\{ r_2\cos\phi_2+r_3\cos(\phi_2+\phi_3)\right\}\cdot\cos\phi_1$$
$$y=\left\{ r_2\cos\phi_2+r_3\cos(\phi_2+\phi_3)\right\}\cdot\sin\phi_1$$
$$z=r_2\sin\phi_2+r_3\sin(\phi_2+\phi_3)$$

Initial positioning of ϕ1, ϕ2 and ϕ3, that is the JSS, JE and JW axes are assumed to be 0, that is parallel in the x axis.

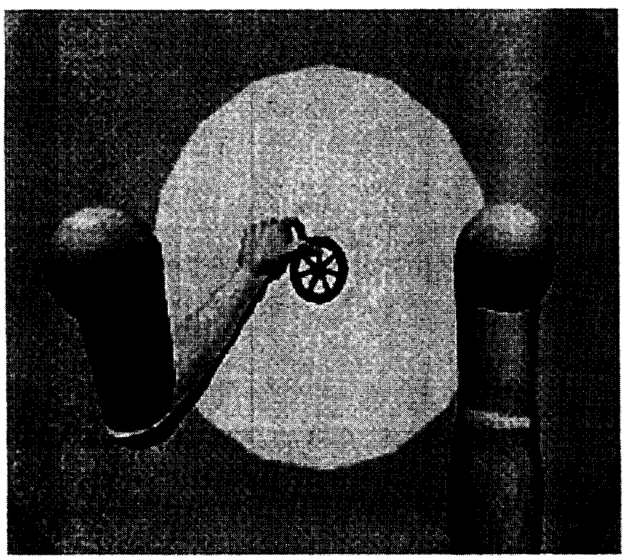
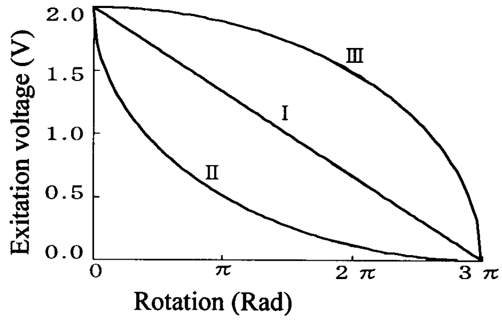


Figure 8. Opening the hatch graphics



Model I $y=-\frac{2}{3\pi}x+2$

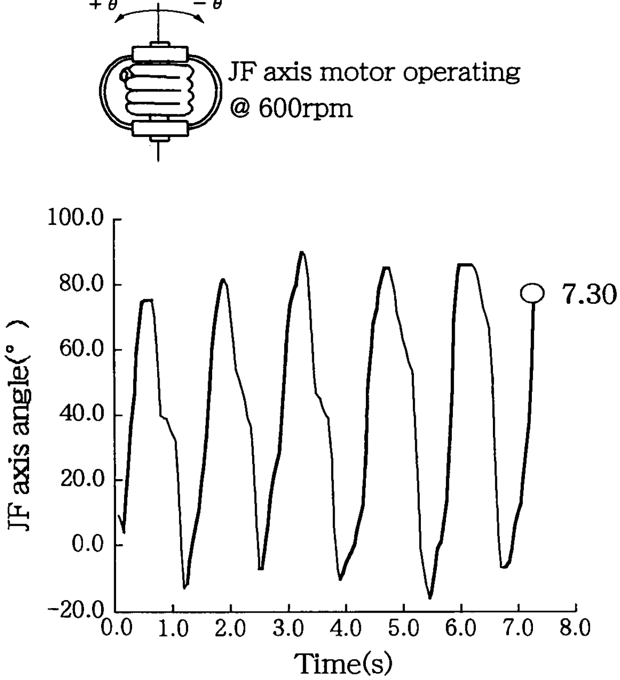
Model II $y=-\sqrt{\frac{36\pi^2-4(x-3\pi)^2}{(3\pi)^2}}+2$

Model III $y=+\sqrt{\frac{4\{(3\pi)^2-x^2\}}{(3\pi)^2}}$

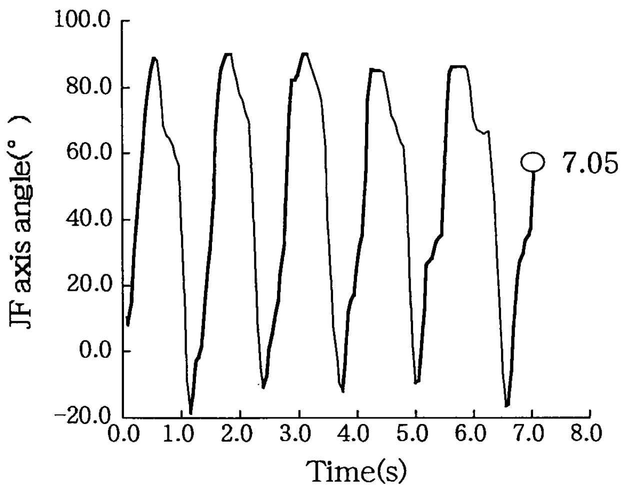
x=Rotation (Rad) y=Excitation voltage (V)

Figure 9. Handle Torque in relation to rotation

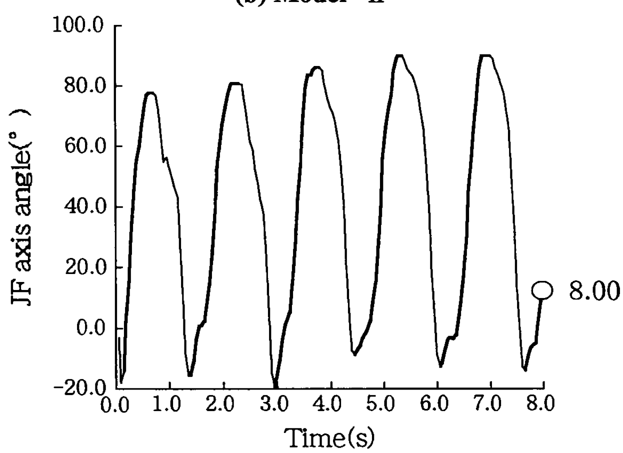
When contact is made with the handle force is imparted on the JF axis (AC servo motor) so as to give the impression of opening a handle. Once the handle is free the hatch can be pushed and with appropriate control of torque on the JE and JSS axes the sense of pushing the hatch open is imparted. Figure 8 shows the graphical image seen by the operator opening the hatch. Figure 9 shows the effective torque on the y axis and rotation position on the x axis. Three different torque/position characteristic curves are shown. Figure 10 displays the progress made by the operators in terms of the JF axis vs time with regard to the implementation of these different torque/position characteristic curves. The point on the curve circled indicates the point at which the handle is considered open and the time taken written to the right of these points. A forth characteristic is also noted for reference purposes, that is the time taken to open the handle when no force feedback is applied to the force display. This simple experiment verified in the virtual world what would be expected from such torque/angle characteristics, that is that with no force applied the handle could be opened most rapidly, while out of the three different torque/position characteristic curves the model II characteristics resulted in the shortest time to open. Thus validating the application of performing simple experiments involving human co-ordination and physical effort in a virtual environment.



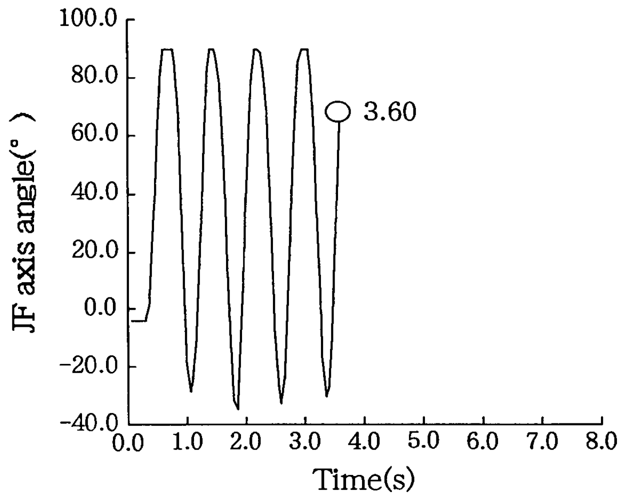
(a) Model Ⅰ



(b) Model Ⅱ



(c) Model Ⅲ



(d) Force display off

Figure 10. Operator results under various conditions

4.2 Virtual ten pin bowling

Bowling is a sport which relys largely on shoulder elbow and wrist action/co-ordination. For this reason the 5 axis force display and VR system have been configured to simulate a ten pin bowling alley, permitting the operator to experience ten pin bowling in a virtual environment. From the simple rolling of a ball a sense of sportsmanship can be imparted and enjoyed. However beyond this the exercise itself can be employed in training/rehabilitation of the respective joints as the operator experiences the natural weight and pendulum effects that would be exerted by a real bowling ball.

A summary of the key movements involved in a bout of 10 pin bowling are as follows:

1. choosing a ball
2. taking hold of the ball lifting it to the rear in which shoulder movement is central
3. finally bowling in a smooth manner by control/co-ordination of the respective shoulder elbow and wrist muscles
4. and release of the ball at an appropriate instant

In order to simulate the above the JW, JE, JSS and JSH axes of the force display must be controlled smoothly and simultaneously. In the virtual environment the operator firstly chooses a ball then upon pressing of the foot switch back the JE axis (rubber actuators RUB1) and the JW axis (pneumatic cylinders) simulate the weight of the ball. With the weight of the ball the operator lifts their arm to the rear (JSS axis), the JSS axis servo-motor provides an opposing torque proportional to the degree to which the ball is raised. Upon initiation of the bowling action the torque is altered appropriately so as not to interfere with the natural pendulum action but rather to assist the smooth movement of the bowl. The ball is released upon the foot switch being pressed in the forward direction.

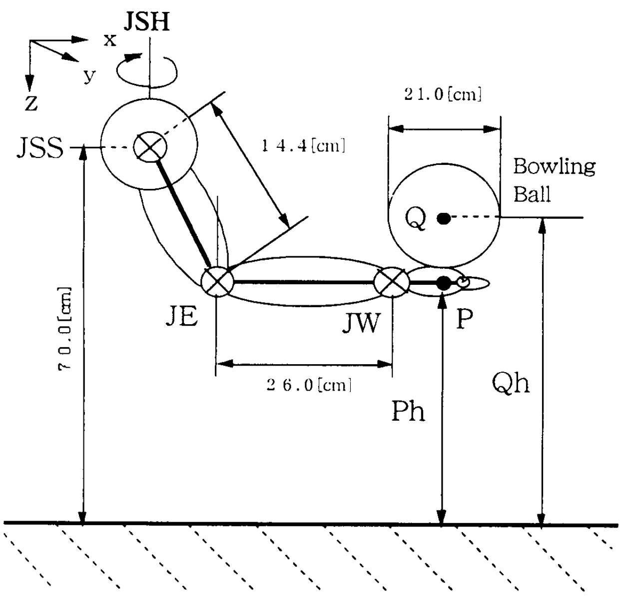


Figure 11. Ball position in relation to the Force display

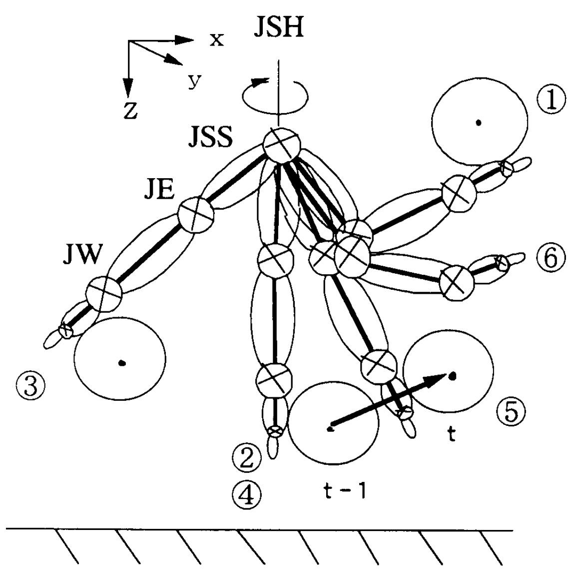


Figure 12. The bowling movement

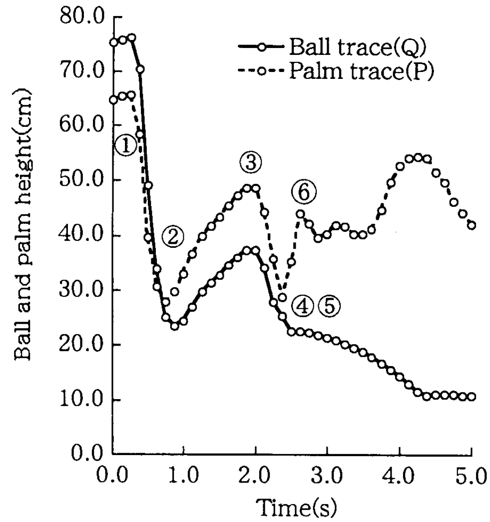


Figure 13. A trace of the ball and palm height wrt time

Figure 11 shows the dimensions and positioning of the bowlers arm and the virtual ball in relation to the force display. Based on the bowling movement and order depicted in Figure 12, Figure 13 is a trace of the ball (center) and the palm of the operator's hand in the vertical plane versus time during the bowl. Figure 14 depicts a scene from the computer graphics when the operator is choosing the ball and figure 15 just after bowling the ball. In the virtual environment the direction and speed of the ball are determined by the shoulders movement (swing direction and speed). If the ball rolls off the defined lane it falls into and rolls down the gutter. The aspect of simulating realistic scattering of the pins in the graphics has yet to be looked into in detail.

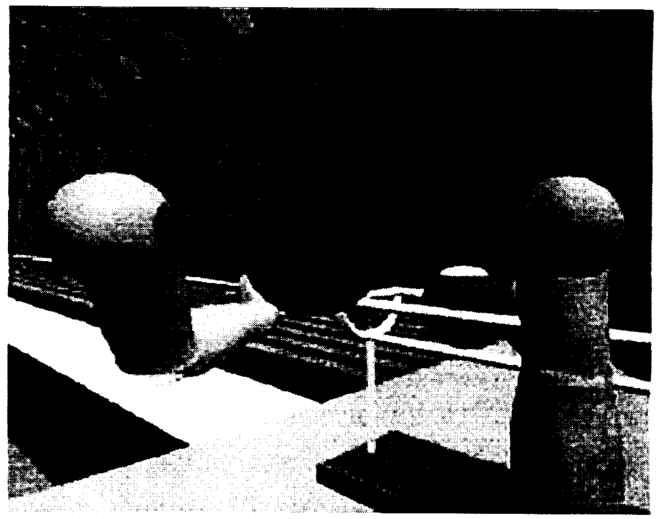


Figure 14. Selection of a ball graphics

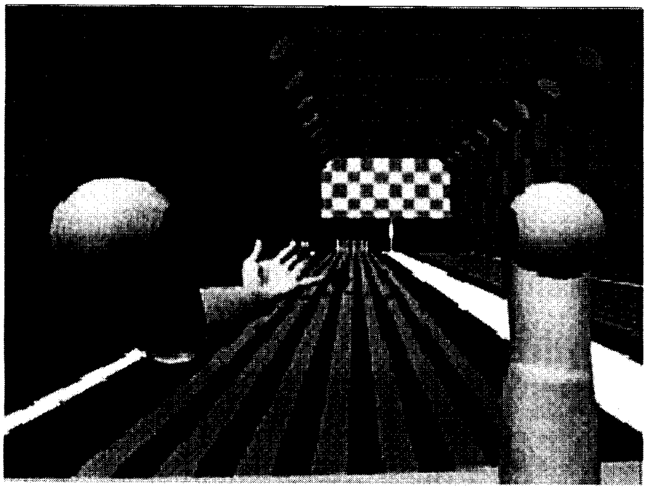


Figure 15. Bowling in the virtual environment

5. Conclusion

A 5 axis force display has been designed, constructed and employed effectively in a number of virtual environments which were developed specifically for the new force display. Until now the force display has been limited to fairly linear push and pull operations, the addition of rotational axes significantly broadens the range of potential applications to which the force display may be employed. In the case of bowling the aspect that requires further work is the simulation of dynamics, particularly in regard to the initial swing down (ref Fig. 12 position 1).

References

[1] T.Takeda and Y.Tsutsui, "Development of a Virtual Training Environment", Symposium on Advance in Robotics, Mechatronics and Haptic Interfaces, the ASME Winter Annual Meeting, DSC-Vol. 49, pp.1-10 (Dec.1993)

[2] T.Takeda and Y.Tsutsui, "On the Computer Simulation of Ball Dribble in the Virtual Environment", 6th International Conference on Human - Computer Interaction HCI International '95 in Tokyo, pp.473 - 478.