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THE DEVELOPMENT OF A BILATERAL INPUT DEVICE FOR USE IN TELEOPERATION

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ABSTRACT

This paper describes the development of a new 6-axis general purpose Hand Controller called the Cartesian mini Master Arm (CmMA). It provides end-point bilateral control in remote manipulative operations. Though the device is primarily intended for use with the NEATER Robot, thus making it a true Telerobot, it can also be used with many other remote handling systems including Hydraulic Servo Manipulators and other industrial robots. Emphasis is placed on the optimisation of the end point bilateral control since the majority of the critical tasks that have to be performed remotely involve the control of manipulator end effector interaction with the object and/or environment. The paper also deals with the rationale used to determine the master arm kinematics, dynamics and control. The principles of operation and control have been tested in simulation and through construction of a mechanism breadboard. A prototype unit will be operational by the end of 1990.

INTRODUCTION

The increased need for remote control operations in the Nuclear Industry has long been recognised, particularly with the beginning of large scale decommissioning and waste management operations of old active facilities and power stations. AEA Technology's philosophy is to adapt proven industrial standards and products wherever possible to meet the general remote handling requirements. As a result, the PUMA 760 Robot has been mechanically upgraded to provide decontaminability, ease of maintenance and tolerance to radioactive environments. The result is NEATER, the Nuclear Engineered Advanced Telerobot.

Even though some routine tasks in a nuclear environment can be carried out robotically by the upgraded robot, the majority of the tasks in operations such as decommissioning are complex and impossible to plan in advance. These tasks therefore demand the incorporation of human judgement, skill and sensory interaction to perform them successfully and safely. The sensory information required by the operator during remote manipulation includes vision, hearing and feel. Advanced telerobotic control therefore requires the development of a suitable input device to command the position and orientation of the remote end effector required by the operator and to feed back the resulting forces exerted on the robot by its environment. The term master arm has traditionally been used to describe a device which gives an operator this direct control over manipulative tasks, and this terminology will be retained. Though the geometry envisaged here is significantly different from that of the traditional manipulator master arm.

The kinematics and dynamics of a master arm basically determine the manoeuvrability of the remote manipulator system [1]. The range of motions in the joints and links and their mechanical properties greatly influence its ease of use and dexterity. The mechanical input impedance characterised by inertia, viscous drag, friction and compliance of the device must be made as low as possible for the operator so that the task forces become transparent. Several different kinematic schemes were studied from a variety of viewpoints but the overall objective was to maximize the dexterity in the wrist. Several master arm designs seeking high dexterity for operators have been proposed and developed by many researchers, for example, polar co-ordinate type by Bejczy & Salisbury [2], vertically articulated (anthropomorphic) type by Kuban et al [3], horizontally articulated type (SCARA) by Hirai & Sato [4] and cartesian co-ordinate type by Matsuhira et al [5], Jacobus et al [6] and many others. It was necessary to find some basis for choosing between these various types.

It must be noted that the relative position of the master arm to the operator is also an important factor as well as the design of the master arm itself. A good master arm must be easily displaceable over a reasonable range of travel and must not restrict the operator's bodily freedom at his chosen workplace (depending on the application, this may be seated at a desk or standing at a viewing window). Since several kinematic arrangements can meet this objective, other requirements for its use were also closely examined to choose the kinematics for the master arm. One such additional need within Harwell was a bilateral command input device which could control either NEATER or the Harwell Hydraulic servo manipulator [7]. It was therefore decided to use a general purpose master arm configuration so that it could be employed with many different types of slave robot or manipulator. The most obvious open kinematic scheme to use is a cartesian co-ordinate frame, which can either be fixed to the end point or in the base of a robot or manipulator. Another advantage of the cartesian kinematic arrangement is that almost all robot controllers can accept external cartesian commands from other peripherals (such as teach pendants, joysticks, etc) over a serial digital communication link for the trajectory control. This will therefore facilitate the use of the already developed inverse kinematic software with singularity control of various robots with little or no modification. Communications can still be a bottleneck and may require improvements in speed for better manual control with force feedback.

KINEMATICS OF THE CARTESIAN MINI MASTER ARM

On the basis of these considerations, the CARTESIAN mini MASTER ARM (CmMA) now under development at Harwell is a desk-top command input device with bilateral characteristics for use in teleoperation. The motions of the CmMA generated by the human operator are read by the Tele-Robotic Controller (TRC) and are scaled, transformed and conditioned as desired to control the robot in either world or tool coordinate frames. Different modes of control such as resolved rate, resolved position and resolved force/torque can be selected at will to perform a remote task conveniently and safely. The wrist, which issues orientation commands, has been designed to provide a one-to-one kinematic correspondence with minimum of inertia, friction and backlash using conventional cable-driven transmissions used in servomanipulators. The parallel linkage scheme was utilized to form a base capable of providing motions in the X and Y directions for a column providing the Z or up/down motion. It was also felt that the X-Y-Z motions of the mechanism must exhibit homogeneous mechanical properties - inertia, friction and stiffness, as far as possible. This has therefore demanded symmetry in the mechanism. The overall mechanism is gravitationally balanced and provision has been made to measure the forces in the X,Y and Z directions so that the excessive inertial resistances in these motions can be compensated for by using feedforward control of the motors. This paper describes the features of this Master arm and its control.

A cartesian kinematic structure can be realised by a variety of linkage arrangements. Fundamentally, there are two possibilities: one using a serial linkage scheme and the other using a parallel linkage scheme. Figure 1 shows the use of a serial linkage scheme for the X-Y motions while figure 2 shows a parallel linkage scheme for the X-Y motions. It can be seen that the parallel linkage scheme is capable of exhibiting homogeneous mechanical properties and provide a uniform structure through which the forces will be transmitted to the origin of the cartesian co-ordinate frame of the master arm. The structure is basically an inverted pendulum in 2-dimensions that requires some form of balancing to prevent it from collapsing. Several schemes based on both active and passive balancing methods were investigated.

The wrist mechanism has been synthesized from the orthogonally pivoted rings or gimbal structure (Fig 3) widely used in gyroscope instruments instead of using the conventional differential wrist gear mechanism. The handle itself, which can be twisted, provides the yaw motion and can be configured for either a seated operator or a standing operator, (Fig 4). The inner gimbal, which has been simplified as a straight bridge for ease of manufacture, enables the generation of pitch command motions while the outer gimbal provides the wrist roll command motions. The motors used for force feedback actuation in these wrist motions have been located remotely to reduce the cumulative inertia as the wrist mechanism is a serially linked structure. Cables are used for the transmission of the mechanical power between the motors and the final wrist motions. Newly available cable chains which exhibit low friction and no backlash were considered but were not chosen because of the constraints on available space and their relatively low stiffness when compared with cables.

The remote location of the motors facilitates the construction of a wrist mechanism with mutually orthogonal motions which are free from any cross-coupling. For example, had the motors been placed directly on the joints, then the wrist yaw motion would have become cross-coupled with the roll motion in the sense that the torque in the roll joint is not only a function of the load in that joint but also a function of the load in the yaw joint. Cross-coupling would cause reduced controllability and inaccurate force reflection unless properly decoupled or filtered in the software and control system. This additional complexity is, therefore, removed by the appropriate mechanical design described above. It can also be noted that while mutually orthogonal linear motions are free from cross-coupling, the mutually orthogonal rotary motions are cross-coupled and also have a kinematic singularity problem.

BILATERAL GRIP HANDLE

The development of the bilateral grip handle has been left as a separate exercise which will be undertaken soon. However, a brief description of its present form is given here since it is an integral part of the master arm presented in this paper.

As stated earlier, the design of the handle for the chosen kinematic arrangement of the master arm depends primarily on the relative position of the master arm to the operator. A seated operator using a desk-top master arm configuration was chosen as the starting point to focus on the design issues. However the selected design is equally applicable to a standing operator configuration. The simple pistol-grip type of handle looked more favourable than the side-by-side thumb and index finger squeeze configuration which is believed to be very fatiguing, Fig 5. The handle must be comfortable to use and non-fatiguing.

A symmetrical handle is preferred in single-handed control systems, so that it can be used by both left-handed and right-handed operators. The operator must be able to move the handle up and down. Hence the grasping must be split and a reaction post provided to prevent the hand grip from slipping during this motion. It is not clear what would be the best combination for functionally splitting the grasping fingers which are normally grouped together. Previous researchers and developers have used both single index finger gripping and two fingers (index and middle finger) gripping. Tichauer's work suggests that when the index finger is used excessively, a defect known as tenosynovitis develops [8]. It affects the ability of the person from flexing his or her index finger easily. It is also needed to push and pull the master arm while maintaining a sensitive bilateral grip of a remotely grasped delicate object. The lateral or left/right motion of the master arm must be relatively easy with the handle free from any control switches on the side of it. The bilateral gripping control must therefore be free from any undesirable coupling between the handle and the master arm kinematics.

Although several examples of handle/grip design have been presented so far, the criteria for designing them is not well documented. However, once it is designed using intuition and common sense, the efficacy of the man-machine interface can be evaluated and design criteria proposed. Fig 6 shows the handle design that has been chosen for the Cartesian mini Master Arm in schematic form.

THE CONTROL SYSTEM

Fig 7 shows a block diagram of the control system under construction. The NEATER robot is fitted with a 6-axis force/torque sensor to measure the end-point forces and torques in the tool co-ordinate frame. The Robot Controller (RC) is the standard VAL-II Control System and the Tele-Robot Controller (TRC) is a PC based system being developed at Harwell. The trajectory control performed by the VAL-II Control System can be modified by the **alter** port which requires displacement updates to the arm in the form of cartesian displacements of the end-point. The commanded joint motions from the cartesian mini master arm are therefore more or less directly compatible with the **alter** port communication interface to the VAL-II trajectory control. Some form of command modification is, however, required to avoid kinematic singularities and joint travel limitations.

The force feedback control system, currently under development, is made to bypass the VAL-II Robot Controller so that communication speed limits which greatly affect the control system performance can be avoided. The slave robot's end-point forces and torques measured by a force/torque sensor are conditioned before they are used as force/torque commands for the master arm control system. Local force feedback on the master arm is derived from the force reflecting servo motor currents. Therefore, no direct force or torque measurements are made in the master arm. It is planned to provide both resolved position and resolved rate control modes so that the operator can easily select the suitable mode he desires to accomplish a task efficiently. In future, it is planned to improve the communication speed to the VAL-II trajectory control system by using an upgraded **slave** port. The **slave** port provides a joint command interface to the VAL-II trajectory control software and also provides joint position feedback information for external use. This enables the evaluation of different types of bilateral servo systems based on position-to-position control and force/torque-to- position control schemes in cartesian workspace before a final selection is made. The joint displacements read from the **slave** port must be converted to cartesian displacements of the robot wrist. The conversion from joint displacements to cartesian displacements is accomplished by using the

Jacobian of the robot kinematics. The Jacobian J(ɵ), which relates velocity in joint space to velocity in cartesian space is position dependent and therefore must be computed each time the robot's position is updated. The Intel's 80386 processor based Tele-robot Controller has proved that this computation can be carried out rapidly so that overall system response is not impaired.

THE STATUS OF DEVELOPMENT AND CONCLUSIONS

A mechanism breadboard has been built to prove the feasibility of implementing the kinematic structure described earlier, Fig 8 (a). The breadboard also assists in the design optimisation process and the subsequent design and manufacture of the prototype. It also enabled us to understand better the complex problems associated with the design of a multi-axis hand controller. Several design changes were made to ensure that the prototype unit will be able to exhibit homogeneous mechanical properties in all directions, Fig 8 (b). The prototype unit will be operational by the end of 1990, and its dexterity will be assessed against simpler devices such as two 3-axis joysticks and the 6-axis Force/Torque ball. The assessment will employ each input device as a Master command unit for NEATER during remote cutting operations.

Force feedback technology and force reflecting command input devices have taken a very long time to evolve to a state where cost-effective and satisfactory systems are viable for wider use. The goal is to demonstrate that such an economically viable command input device can be developed and be made available for use on a variety of applications in the near future.

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APPENDIX

ELEMENTS OF CmMA'S TARGET SPECIFICATIONS

The choice of the Master Arm's working volume has been based on the information and experience on other manual controllers.

Motion Range:	
o Translations - X,Y,Z	± 115mm
o Orientations - Roll, Pitch, Yaw	$\pm 90^o$
Force/Torque Range:	
o Forces - F_x, F_y, F_z	25N
o Torques - T_x, T_y, T_z	2.5Nm
Small Signal Bandwidth:	
o Position servo loop (2 mm/2 deg):	10Hz
o Force/Torque Servo loop (0.1 N/0.1Nm)	30Hz
Force/Torque Friction Threshold:	
o Force (X,Y,Z)	0.1N
o Torque (wrist)	0.02Nm

Mechanical Input Impedance:

o Translations (force to velocity)	$1.0 N/m.sec^{-1}$
o Rotations (torque to speed)	$0.05 Nm/rad.sec^{-1}$

NOTE: The inertial resistances and viscous drags along each degree of freedom will be evaluated once the prototype unit is built and tested.

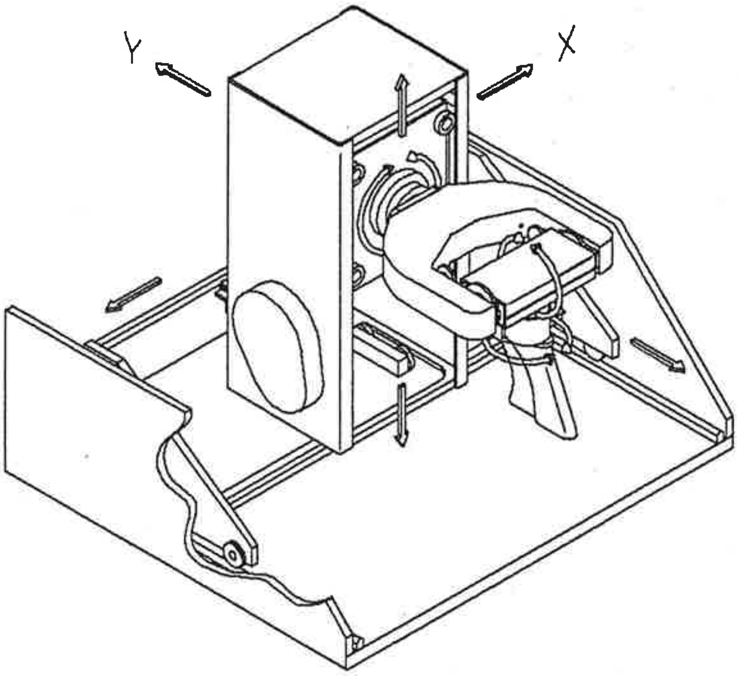

Fig 1 REALISATION OF X-Y MOTIONS
USING SERIAL LINKAGE STRUCTURE

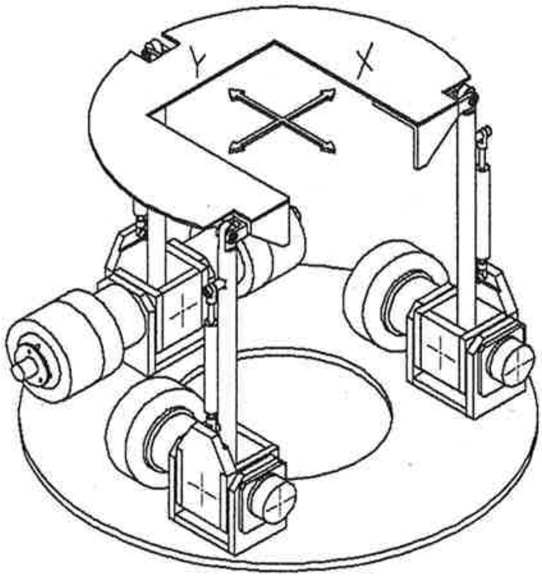

Fig 2 REALISATION OF X-Y MOTIONS
USING PARALLEL LINKAGE STRUCTURE

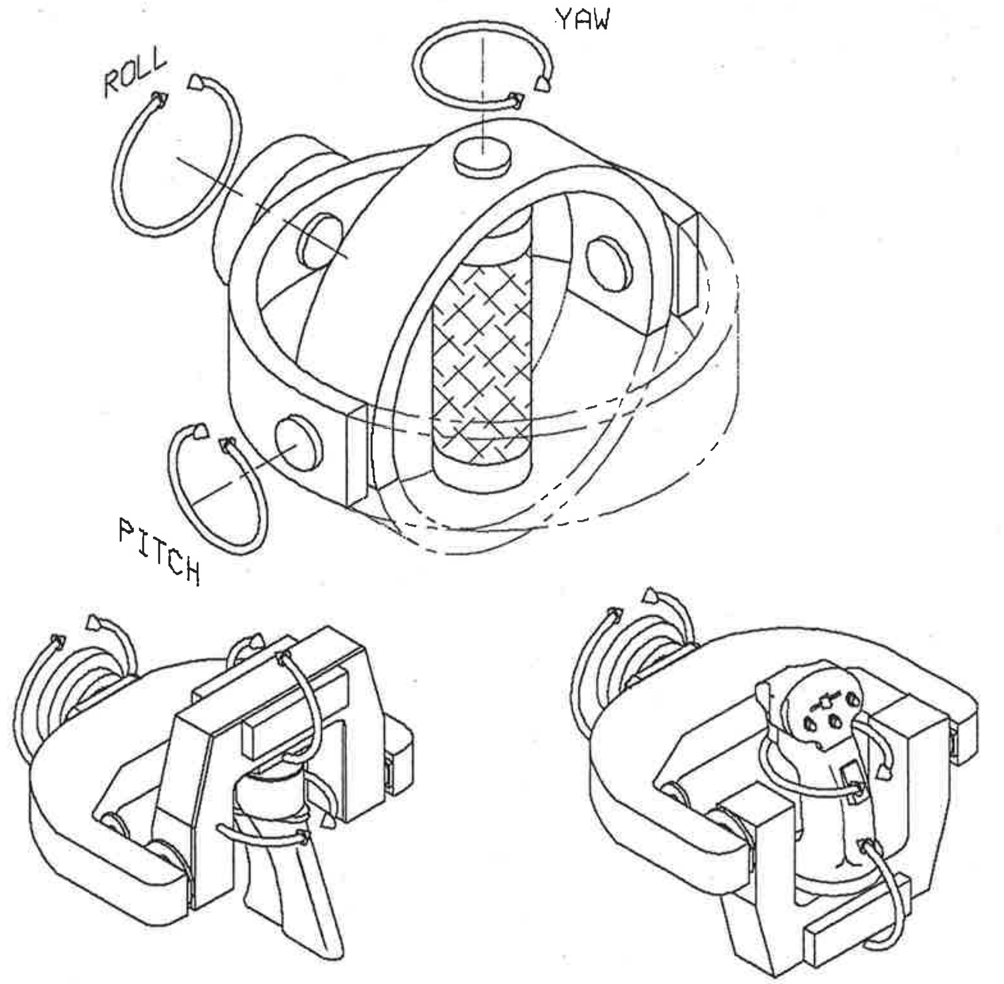

Fig 3. SYNTHESIS OF ORTHOGONAL 3-AXIS WRIST STRUCTURE USING GIMBLALS (PIVOTED RINGS)

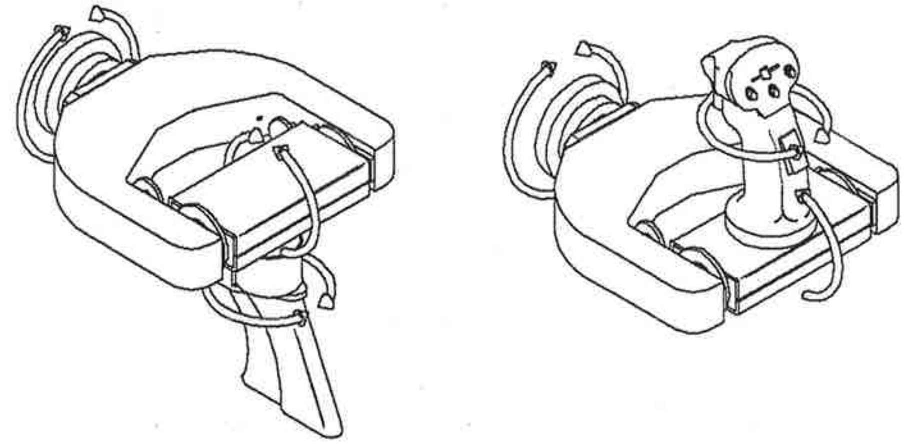

Fig 4. SIMPLIFIED WRIST CONFIGURATION FOR SEATED AND STANDING OPERATORS

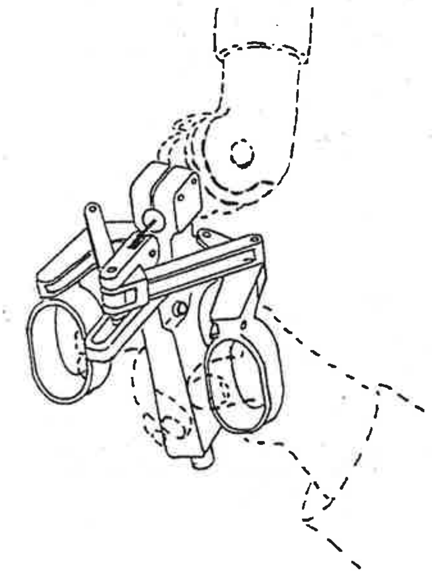

Fig 5. PARALLEL GRIP
USING THUMB &
INDEX FINGERS

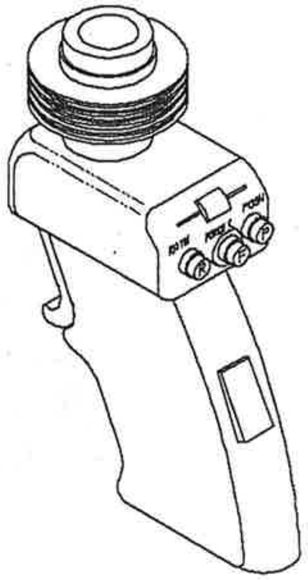

Fig 6. PISTOL GRIP
USING MIDDLE &
INDEX FINGERS

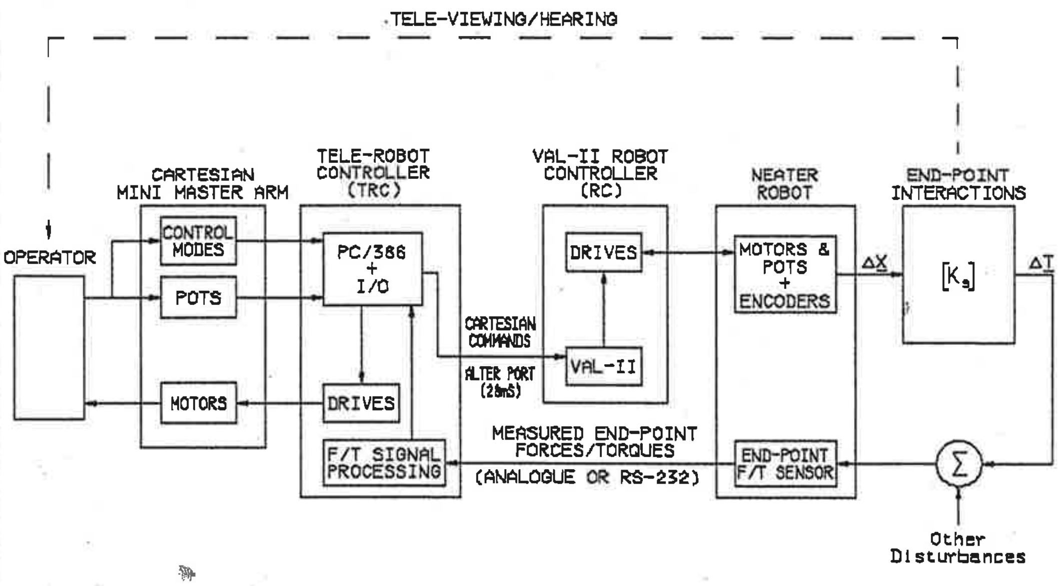

Fig 7. SCHEMATIC BLOCK DIAGRAM OF THE TELE-ROBOT CONTROL SYSTEM

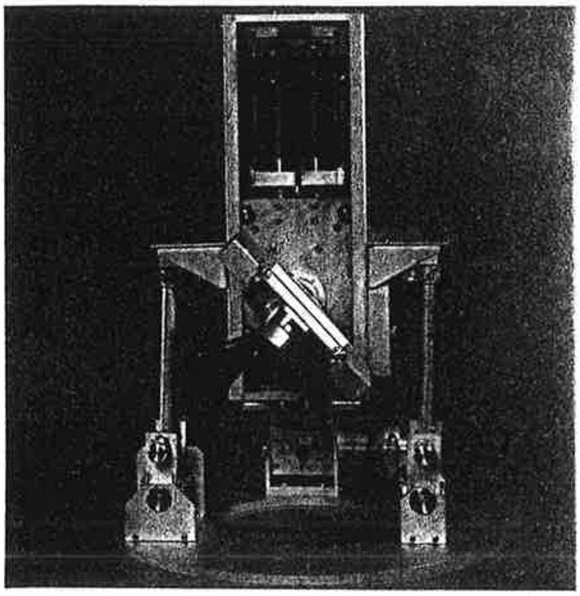

Fig 8(a). CmMA - BREADBOARD MECHANISM

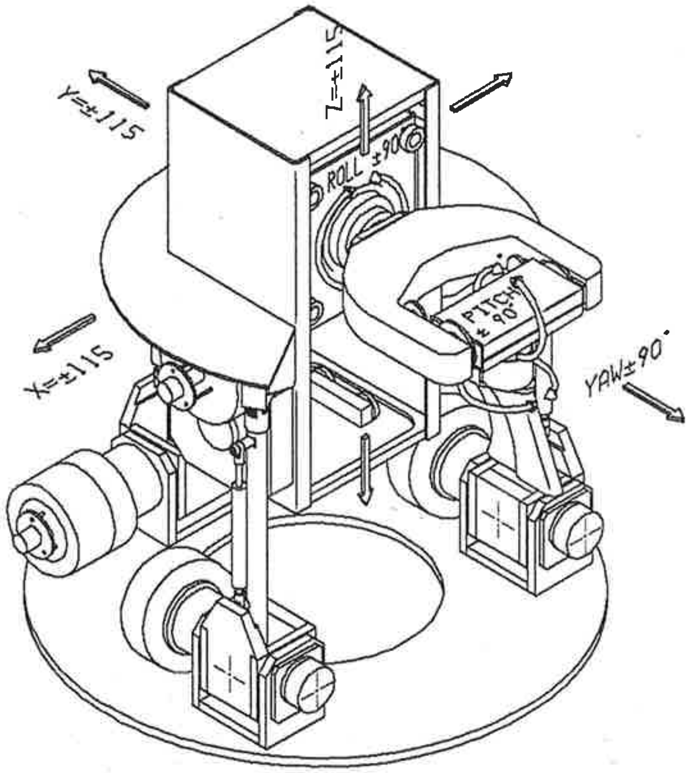

Fig 8(b). CmMA - PROTOTYPE DESIGN
(Patent Applied for)