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A New Active Virtual Pivot Six-Degree-of-Freedom Hand Controller for Aerospace Applications

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Abstract

During 1989 a new six-degree-of-freedom (6-DOF) active hand controller concept was designed and constructed based on the concept of a "virtual pivot." This concept, labeled VPHC, was first demonstrated in a 1985 study by a member of the design team, and a patent was issued in 1990. Operator control input occurs via a force/torque sensor rigidly mounted to the handgrip. Sensed force/torque signals are used by microprocessors to generate motor drive control for each of six independently controlled motors mounted on the three-legged mechanism. The control microprocessor uses input biasing and rate-feedback motor controllers to generate the sensed feel of virtual springs and deadbands found in more conventional designs.

An important advantage of this design is that the location of the virtual pivots, reflective forces and torques, breakout force levels, sensed spring rates, operating modes, etc., can be changed simply by changing the software. This approach yields an autonomous VPHC that can easily adapt itself to an individual operator (by software extension). A proof-of-concept version has been demonstrated, and further improvements are currently being studied and implemented.

Introduction

In the space-based platforms planned for the Space Station and Lunar-Mars initiative, a significant range of activities will have to be performed using hand controls. These include:

- Telerobotics using crane-type arms, which have relatively crude end-effectors.
- Telerobotics using dextrous manipulators, which have end-effectors with more degrees of freedom.
- Remotely piloted vehicles.
- Coordinated control of two robot arms simultaneously.

Given that the task demands for these activities are quite different, it is appropriate to provide several kinds of hand controllers; however, space constraints and the need for commonality (to reduce training/retraining time and increase generalization) have led us to examine the feasibility of using a single controller for all tasks. Such a controller will have to be flexible and easy to reprogram as the task demands dictate, accommodate the needs of a diverse user population, and require minimal space. In addition, it will have to be reliable and provide for graceful degradation. Our design is a unique invention embodying the virtual pivot concept first shown by us in 1985. Our 1989 initiative work resulted in a successful demonstration of this concept expanded to six degrees of freedom.

General Design Goals

Our 1989 goals were to construct an effective and efficient 6-DOF hand controller that incorporates system engineering principles, including human factors requirements, and that has broad applicability for both space-based and ground/air-based activities. We intended to use the virtual pivot concept invented during our 1985 research initiative. The design approach required us to:

- Implement the virtual pivot concept expanded to a 6-DOF capability.

- Achieve unconstrained 6-DOF motion with ± 3.8 cm (± 1.5-in.) translations and ± 350 mr (± 15 deg) angular displacements.

- Provide both rate and position mode operations.

- Allow reasonable task performance under degraded conditions (i.e., use a force/torque sensor as a force stick if the virtual pivot hand controller [VPHC] motors fail).

General Design Implementation

The VPHC (see Figure 1) is intended to serve as a general-purpose, adaptable force feedback 6-DOF hand controller for a variety of space applications. System equations were developed that relate potentiometer measurements to the inferred position and attitude and implement feel dynamics to the human operator in response to translation or rotation of the hand grip. The VPHC uses input biasing to generate the sensed feel of springs and mechanical deadbands (see Figure 2). Operator control input occurs via a force/torque sensor rigidly mounted under the handgrip. This sensor responds to 6-DOF linear forces and moments (applied to the handgrip by the operator) and in turn supplies six signals representing Cartesian force and moment vectors. This force/torque sensor also provides backup capability to the VPHC as a force stick if the motor drives fail.

The VPHC system equations were derived to convert the measurements of three leg lengths and six angles into grip platform attitude Euler angles and position from the origin of the platform coordinate system. An initial analysis of the force/moment equations showed that mechanical lockup cannot occur over the allowed range of motion. Relationships between desired angular and linear velocities of the platform and measurements of leg extension and leg angles were also derived (solving the reverse kinematics problem). These straightforward algorithms efficiently generate the command inputs to a closed-loop control system in the real-time mechanization.

Basic Design Features

Figure 3 is a sketch of the hand control mechanical design. There are three ball joints at the top of telescoping legs. Leg lengths are measured by linear potentiometers. Also shown are three linear screw drive motors in the legs and three motors and shaft angle pickoffs used to determine the spherical coordinates for each leg. In addition, there is a 6-DOF force/torque sensor mounted under the platform to measure operator input for 6-DOF rate control. The handgrip is mounted on the force/torque sensor. During system calibration, the fixed displacement vector (from the origin of the platform coordinate frame) of the operator's wrist joint is to be estimated. Figure 4 shows the vector relationships between the base and platform coordinate frames.

Processor Interface—The signal interface required to determine platform orientation and translation in six degrees of freedom consists of nine potentiometer measurements (three per leg) that define the three position vectors of the platform's three fixed ball joints with respect to the three base leg pivot points. The processor must then return the three Euler angles and the three linear translations from nominal platform origin. In addition, the force/torque sensor inputs are used in either position or rate mode to command a 6-DOF velocity that the motorized legs and shaft drives are to deliver. Hence, the processor must first solve the geometric task of computing orientation and translation and then compute the requisite leg rotational and linear velocities that result in the commanded system state.

Kinematic Equations—Kinematic solutions to the handgrip platform Euler angles (defining attitude angles) and linear displacements from the center of the coordinate frame are uniquely obtained by using nine potentiometers rather than a smaller number (theoretically possible). The telescoping legs (whose lengths are actuator driven) are attached to the platform by ball joints and to the base by double-gimbaled motorized joints. The outer gimbals are rigidly attached to the base, are motor driven, and cause a roll motion about the leg's motor axis of rotation. The outer gimbal axis defines the leg coordinate frame x axis for each of the three legs. These three axes are each oriented along the radial directions with respect to the center of the base. This results in the forward base point having its motor axis along the x axis of the base coordinate frame. The azimuth angles to the other two base points have constant values of $\frac{2}{3}\pi$ and $\frac{4}{3}\pi$ radians (120 and 240 deg). Inner gimbals allow rotation about the respective leg pitch axes. Letting the lengths of the three legs d_i, where i = 1, 2, 3, be defined by $0 < d_{i_{min}} < d_i < d_{i_{max}}$, then the position vectors of the platform's ball joints with respect to the base frame S_B are

$$\vec{P}_i = E_i(\psi_0)E(\theta_i,\phi_i)\begin{bmatrix} 0 \\ 0 \\ d_i \end{bmatrix} + \vec{P}_{B_i}\,;\, i = 1,2,3 \tag{1}$$

where

$$E(\theta_i,\phi_i) = \begin{bmatrix} \cos\theta & 0 & \sin\theta_i \\ \sin\theta_i \sin\phi_i & \cos\phi_i & -\cos\theta_i \sin\phi_i \\ -\sin\theta_i \sin\phi_i & \sin\phi_i & \cos\theta_i \cos\phi_i \end{bmatrix} \tag{2}$$

and

$$E_i(\psi_0) = \begin{bmatrix} \cos\psi_0 & -\sin\psi_0 & 0 \\ \sin\psi_0 & \cos\psi_0 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \psi_0 = 0, 120, 240 \text{ deg for } i = 1,2,3 \tag{3}$$

Processor Overview—The processor is a Motorola VMEbus 68020 single-board microcomputer housed in a standard Motorola chassis with several analog-to-digital interface cards. Six tachometers on the three legs measure motor speeds of shaft and leg-extending motors (two per leg). Potentiometers measure leg extension and the two shaft angles of each leg (nine potentiometers in all). Rate and position control modes differ. In the position mode, removal of grip force/torque commands from the operator causes the VPHC to remain at its latest attained attitude and linear displacement. Removal of input in the rate mode will cause a return to the initial displacement origin. Any of the six degrees of freedom may be locked out if desired. Software stops are provided to prevent the system from running into hard stops, which might cause damage. Figure 5 is an overview diagram of the control channels. The reverse kinematics and platform Euler angle computations are discussed in the next two subsections.

Geometric Relationships—Defining the position vectors of the pivots by R_{B_i} and R_{P_i}, where i = 1, 2, 3, in the two separate frames S_B (the base frame) and S_P (the platform frame) results in

$$\overline{R}_{B1} = \begin{bmatrix} r_B \\ 0 \\ 0 \end{bmatrix}; \overline{R}_{B2} = \begin{bmatrix} -r_B/2 \\ (\sqrt{3}/2)r_B \\ 0 \end{bmatrix}; \overline{R}_{B3} = \begin{bmatrix} -r_B/2 \\ -(\sqrt{3}/2)r_B \\ 0 \end{bmatrix}$$

$$\overline{R}_{P1} = \begin{bmatrix} r_P \\ 0 \\ 0 \end{bmatrix}; \overline{R}_{P2} = \begin{bmatrix} -r_P/2 \\ (\sqrt{3}/2)r_P \\ 0 \end{bmatrix}; \overline{R}_{P3} = \begin{bmatrix} -r_P/2 \\ -(\sqrt{3}/2)r_P \\ 0 \end{bmatrix} \tag{4}$$

The vector $\overline{R}_C$ defines the origin of the S_P frame and is given by

$$\overline{R}_C = \tfrac{1}{3}\sum_{i=1}^{3}\left(\overline{R}_i + \overline{R}_{Bi}\right) \tag{5}$$

or

$$\overline{R}_C = \tfrac{1}{3}\sum_{i=1}^{3} E_1(\psi_0)\begin{bmatrix} -d_i \sin\theta_i \\ d_i \cos\theta_i \sin\phi_i \\ -d_i \cos\theta_i \cos\phi_i \end{bmatrix} = \tfrac{1}{3}\sum_{i=1}^{3}\overline{R}_i \tag{6}$$

since the sum $\sum \overline{R}_{Bi} = 0$

Referring to Figure 4, the platform $\hat{X}_P$ unit vector is directed from the center toward P_1. The $\hat{Y}_P$ unit vector is parallel to the line from P_3 to P_2. Then

$$\hat{X}_P = \left(\tfrac{1}{r_P}\right)\left[\overline{R}_1 - \overline{R}_C\right] = \left(\tfrac{2}{3}\overline{R}_1 - \tfrac{1}{3}(R_2 + R_3)\right)$$

$$\hat{Y}_P = \left(\frac{1}{\sqrt{3}\, r_P}\right)\left[\overline{R}_2 - \overline{R}_3\right] \tag{7}$$

$$\hat{Z}_P = \hat{X}_P \times \hat{Y}_P = \left(\frac{2\sqrt{3}}{9\, r_P^2}\right)\left[\overline{R}_1 \times \overline{R}_2 + \overline{R}_2 \times \overline{R}_3 + \overline{R}_3 \times \overline{R}_1\right]$$

The direction cosines of the X_P, Y_P, and Z_P unit vectors are the components of the preceding vector equations. The Euler rotation matrix from S_B to S_P is then

$$E_{P/B} \equiv \begin{bmatrix} \hat{X}_P \cdot \hat{X}_B & \hat{Y}_P \cdot \hat{X}_B & \hat{Z}_P \cdot \hat{X}_B \\ \hat{X}_P \cdot \hat{Y}_B & \hat{Y}_P \cdot \hat{Y}_B & \hat{Z}_P \cdot \hat{Y}_B \\ \hat{X}_P \cdot \hat{Z}_B & \hat{Y}_P \cdot \hat{Z}_B & \hat{Z}_P \cdot \hat{Z}_B \end{bmatrix} = \{e_{ij}\} \tag{8}$$

All information concerning the relative attitude orientation between the VPHC base and platform frames is contained in the Euler matrix $E_{P/B}$. Euler angles can be defined in 24 different ways depending on the sequence of rotations (in a positive sense about each of three axes). There are 12 permutations starting with either frame S_P or S_B, or 24 total. Each set of three angles is not interchangeable (except for very small rotations). Each set does, however, result in the same rotation of one frame to another when applied in its specific sequence.

The following set arises from a yaw rotation about the S_B z axis followed by a pitch rotation about the y axis and a final roll about the x axis:

$$\begin{aligned} \psi_P &= \tan^{-1}(e_{12}/e_{11}) = \text{Yaw} \\ \theta_P &= \sin^{-1}(-e_{13}) = \text{Pitch} \\ \phi_P &= \tan^{-1}(e_{23}/e_{33}) = \text{Roll} \end{aligned} \tag{9}$$

Each rotation assumes the right-hand rule for positive sense. The inverse transformation performs a roll-pitch-yaw transformation (in that order) and is not uncommon in the aircraft industry.

Platform Velocity Equations—Tachometers mounted on the VPHC legs and roll axis shafts are used in a velocity feedback controller that drives each motorized leg to null a separate commanded velocity. These six velocities are in turn computed according to the six signals from the Lord force/torque sensor (after biasing to provide reflected force or torque dynamics for the operator).

At present, handgrip force signals are interpreted as referenced to the base coordinate frame as a linear velocity command. The torque moments, however, are presently interpreted as referenced to the platform coordinate frame as an angular velocity command. The coordinate system used is arbitrary and can be easily redefined in processor code and provided later as an optional VPHC operating mode if desired.

The inertial velocity of each leg is composed of the linear velocity of the platform's center summed with the rotational velocity about the center, that is

$$\vec{V}_i = \frac{d}{dt}\vec{R}_i = \vec{V}_C + \vec{\omega}_P\left(\vec{R}_i - \vec{R}_C\right); i = 1,2,3 \tag{10}$$

where all quantities are assumed to be expressed in the same coordinate system. Differentiating the left side (using the previous equation for R_i) results in

$$\vec{V}_i = \frac{d}{dt}\vec{R}_i = E_1(\psi_0)\left\{\frac{d}{dt}\left[E_i(\theta_i, \phi_i)\begin{bmatrix} 0 \\ 0 \\ -d_i \end{bmatrix}\right]\right\} = \vec{V}_C + \vec{\omega}_P\left(\vec{R}_i - \vec{R}_C\right); i = 1,2,3 \tag{11}$$

or

$$\vec{V}_i = \Omega_i(\psi_0, \theta_i, d_i)\begin{bmatrix} \dot{\theta}_i \\ \dot{\phi}_i \\ \dot{d}_i \end{bmatrix} = \vec{V}_C + \vec{\omega}_P\left(\vec{R}_i - \vec{R}_C\right); i = 1,2,3 \tag{12}$$

Then

$$\begin{bmatrix} \dot{\theta}_i \\ \dot{\phi}_i \\ \dot{d}_i \end{bmatrix} = \Omega_i^{-1}\left[\vec{V}_C + \vec{\omega}_P\left(\vec{R}_i - \vec{R}_C\right)\right]; i = 1,2,3 \tag{13}$$

In the above equation, only the expressions for leg roll and length rates are of interest as the VPHC leg pitching rates are automatically driven by mechanical constraints. This solution requires inversion of a 3 by 3 matrix, where

$$\Omega_i(\psi_0,\theta_i,\phi_i,d_i) = E_i(\psi_0)\begin{bmatrix} 0 & -d_i\cos\theta_i & -\sin\theta_i \\ d_i\cos\theta_i\cos\phi_i & -d_i\sin\theta_i\sin\phi_i & \cos\theta_i\cos\phi_i \\ d_i\cos\theta_i\sin\phi_i & d_i\sin\theta_i\cos\phi_i & -\cos\theta_i\cos\phi_i \end{bmatrix}; i = 1,2,3 \qquad (14)$$

The above platform angular velocity vector input commands, $\vec{\omega}_P$, are referenced to S_B; if they are referenced to S_P instead, they are simply converted by the inverse Euler transformation as follows:

$$\vec{\omega}_P = \begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix}_B = E_{P/B}^{-1}\begin{bmatrix} \omega_{X_c} \\ \omega_{Y_c} \\ \omega_{Z_c} \end{bmatrix}_P \qquad (15)$$

The inverse Euler matrix is simply the transpose of the matrix since the coordinate frame is orthogonal and Cartesian.

Conclusions

The unique demonstrable feature of the VPHC is that the sensed location of the pivot point can be set arbitrarily. It can be set through the center of the grip, above or below it, or centered inside the operator's wrist. For example, with a pivot point below the grip, it would act like a conventional military aircraft hand controller, with the pivot point where the stick attaches to the floor. However, with the pivot point above the grip, the top of the grip seemingly would be attached to a point above it, and the entire device would be swinging freely below it. This programmable pivot point allows maximum flexibility and adaptability. These changes can be made simply by entering the appropriate software commands.

The VPHC is an active device, using motors to control forces and torques. (A passive controller uses springs instead of motors.) This offers two additional features that are important for a hand controller that must be used in a variety of situations:

- The operating characteristics can be changed simply by changing the software. Thus, breakout forces, the degrees of freedom available, and spring rates, etc., can be modified without changing any hardware.

- Based on information from the object being controlled, the operator can be given feedback through the grip. This capability is called force reflection and usually involves providing tactile feedback through the grip when the controlled object (e.g., a robot arm) contacts the target (or other) object.

The combination of a programmable virtual pivot point with an active hand controller offers the unique capability to configure the hand controller to match the demands of the current task and to satisfy the wishes of a particular user.

Summary

In 1989, we extended the 1985 passive single-axis concept and invented a 6-DOF orthogonal-axis active hand controller. Figure 1 illustrates the change. The enhanced design has two key features:

- A motor-driven mechanical configuration that allows independent 6-DOF motions consisting of three linear translations and three angular rotations referred to Cartesian orthogonal axes. Motion is constrained to $\pm$3.8 cm ($\pm$1.5 in.) and/or $\pm$350 mr ($\pm$20 deg) about the origin of the virtual pivot coordinate frame.

- Motor-driven force feedback (microprocessor controlled) that replaces spring centering. Gradients of forces or torques vs. displacements (in each of six axes; see Figure 2) are stored as parameters that can be modified by keyboard input. This modification provides adaptability or programmability of key hand controller operating characteristics: (1) sensed (virtual) pivot axis locations and range of motion in each axis; (2) sensed spring force reflection or the feel of the instrument (force/displacement gradients); (3) the capability, if desired, to implement bilateral force feedback from the system being controlled (via motor control feedback) to the human operator; and (4) the capability of operator-mode control to introduce menu-driven commands (via the VMEbus single-board computer).

Many other uses for an adaptable hand controller exist, such as control of fixed-wing aircraft (e.g., the National Aerospace Plane) and rotary-wing aircraft (e.g., the Advanced Apache), telerobotics for a variety of applications (e.g., radiation cleanup sites), and underwater applications both for vehicle maneuvering and robotic manipulation.

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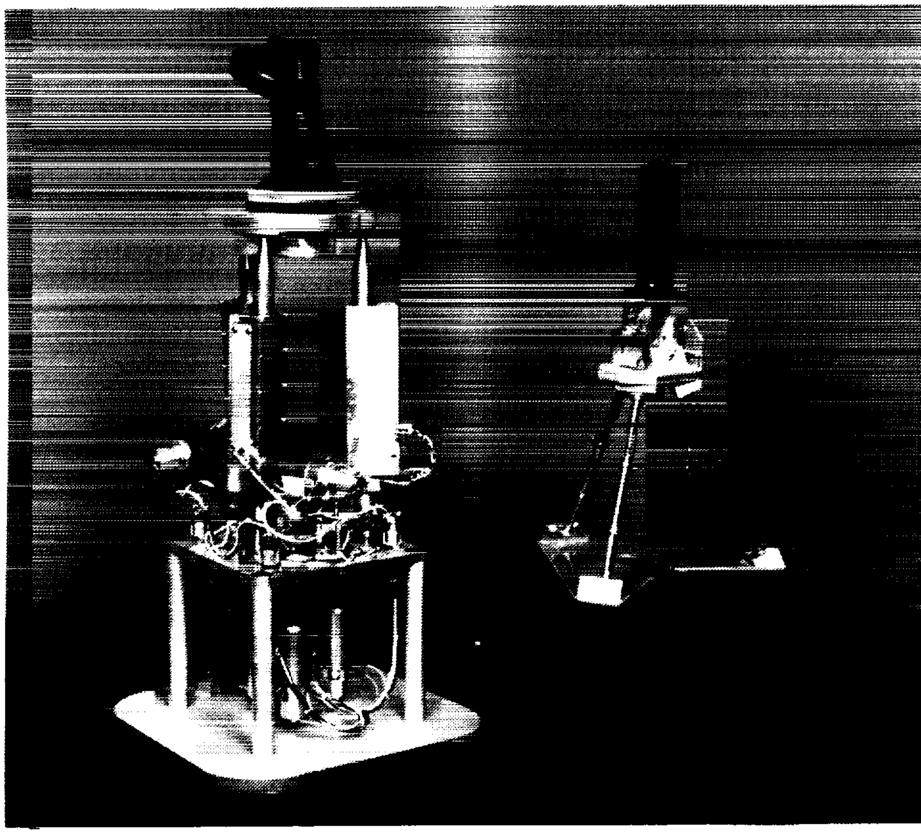

Figure 1. 1989 6-DOF VPHC Design (left) and Original 1985 Single-DOF VPHC Design (right)

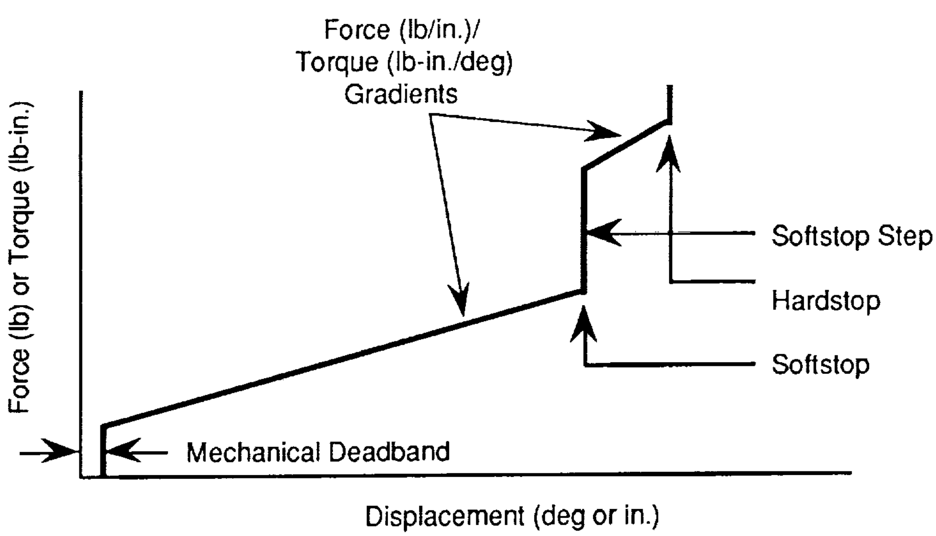

Figure 2. Handgrip-Applied Force/Torque vs. Displacement Profiles

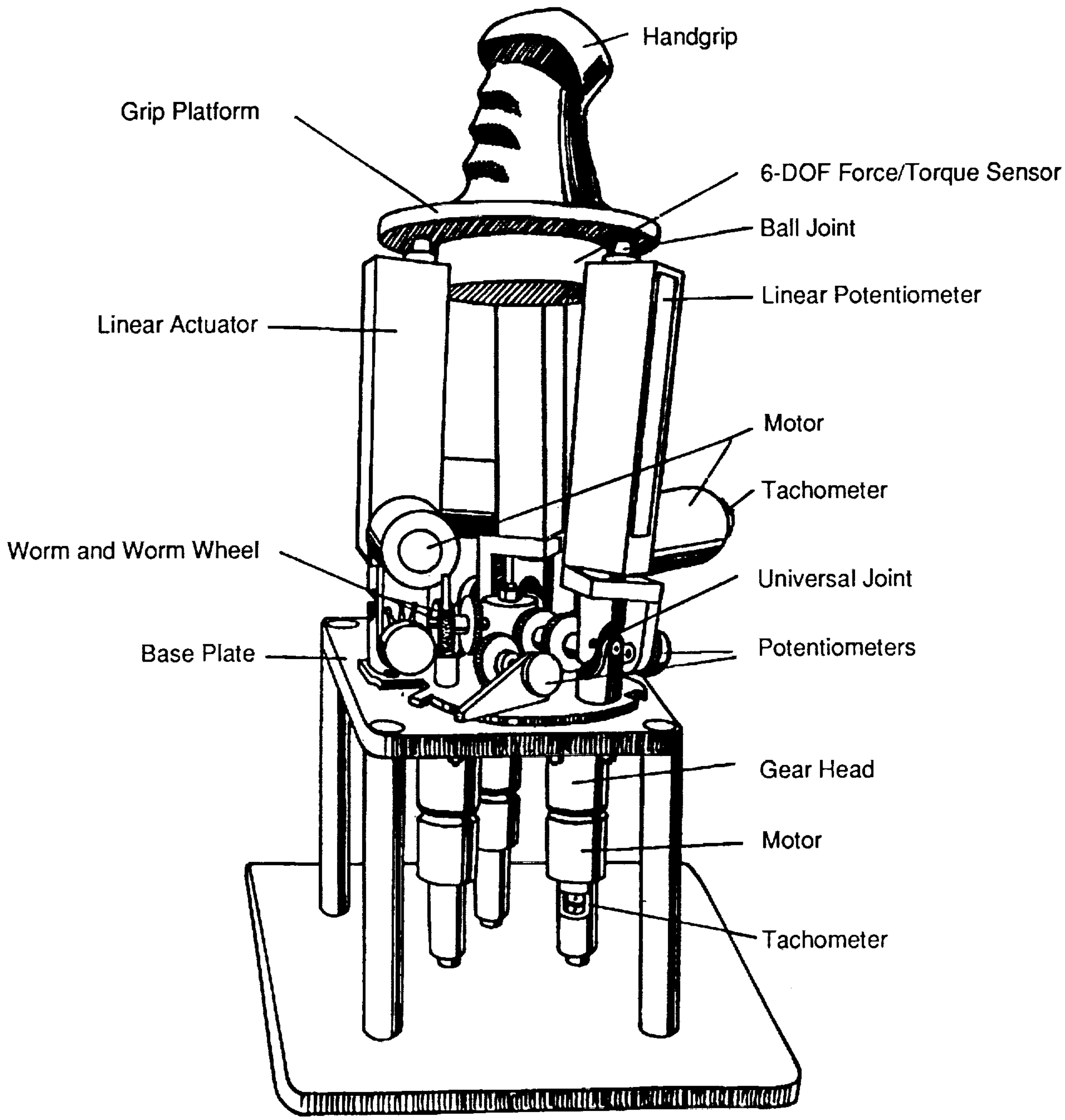

Figure 3. Hand Controller Mechanical Design

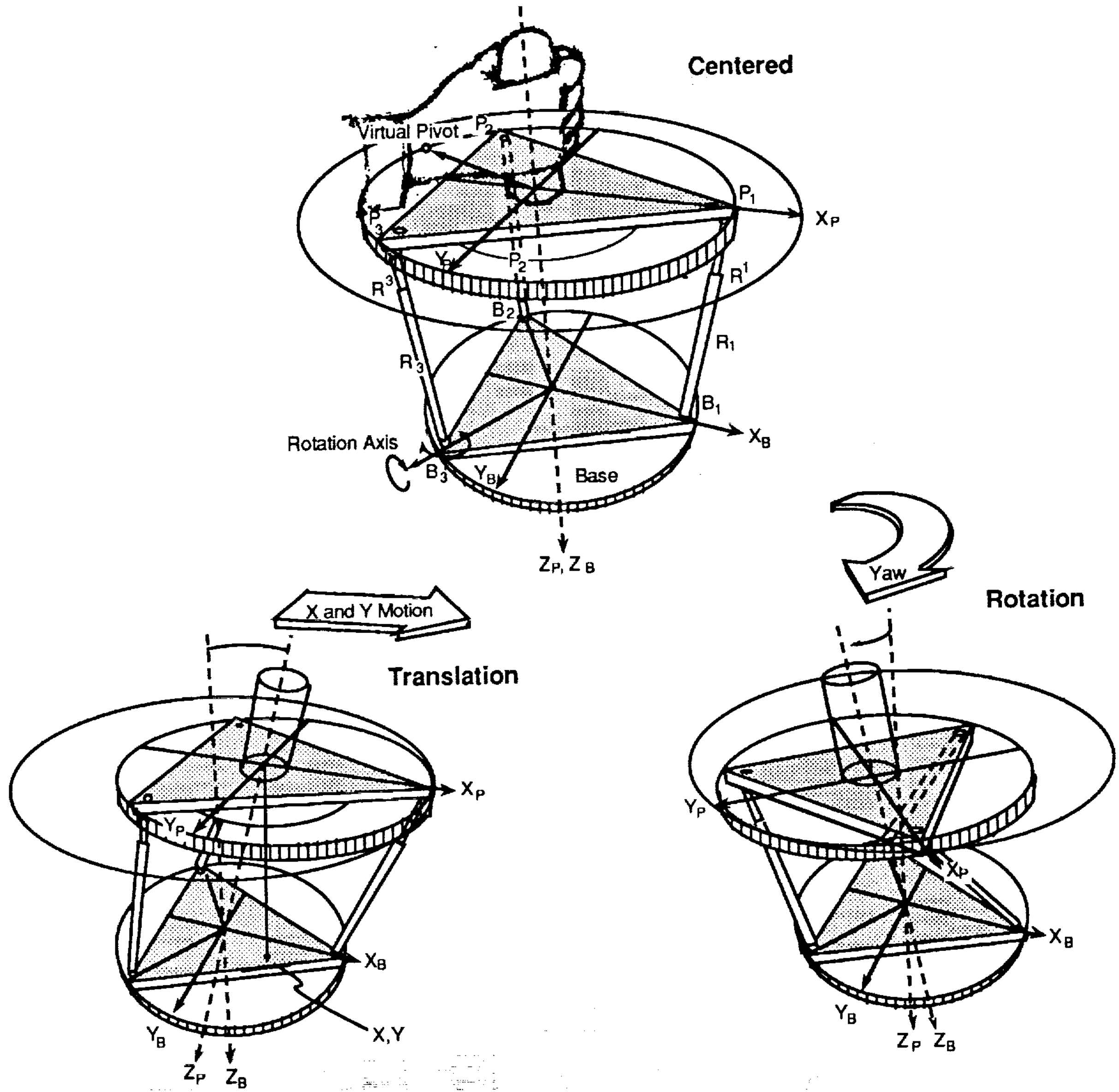

Figure 4. Vector Relationships between Base and Platform Coordinate Frames

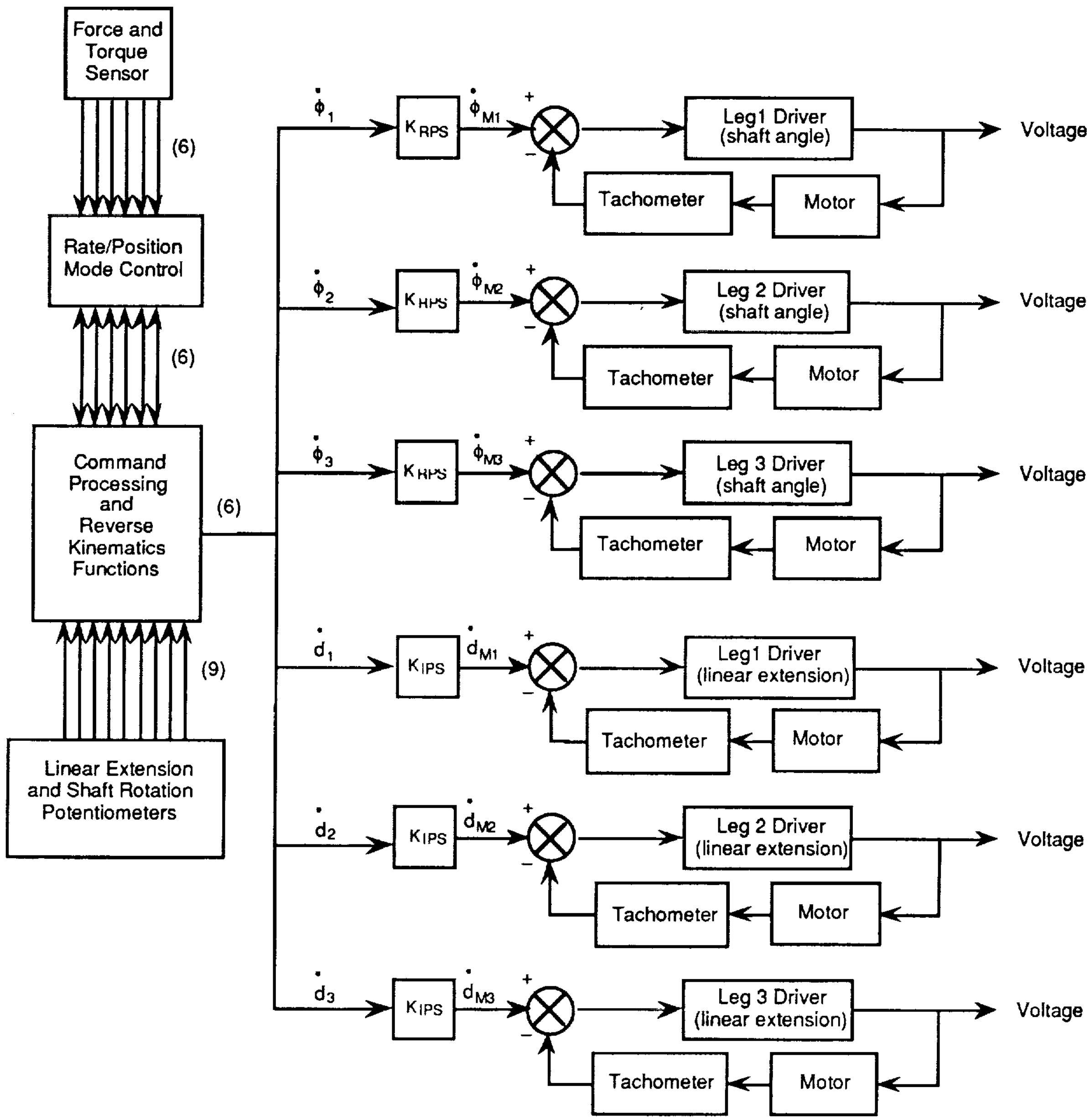

Figure 5. VPHC Motor Control Channels