KINESTHETIC FORCE/MOMENT FEEDBACK VIA ACTIVE EXOSKELETON[1]

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Abstract

Theoretical control algorithms are developed and an experimental system is described for 6-dof kinesthetic force/moment feedback to a human operator from a remote system. The remote system is a common six-axis slave manipulator with a force/torque sensor, while the haptic interface is a unique, cable-driven, seven-axis, force/moment-reflecting exoskeleton. The exoskeleton is used for input when motion commands are sent to the robot and for output when force/moment wrenches of contact are reflected to the human operator. This system exists at Wright-Patterson AFB. The same techniques are applicable to a virtual environment with physics models and general haptic interfaces.

Introduction

Teleoperation of remote manipulators is greatly enhanced by using a force-reflecting input device. This force/moment haptic feedback increases the sense of telepresence (where the user feels part of the remote or virtual environment) by enabling the operator to feel through the force-reflecting master the wrench (6-dof forces and moments) exerted by the slave manipulator on the environment. The Human Sensory Feedback (*HSF*) Laboratory at Wright-Patterson *AFB* has a world-class capability for experimentation in force-reflecting teleoperation for Air Force and *NASA* applications: The unique *FreFlex* force reflecting exoskeleton master (Odetics, 1992) and a *Merlin* industrial manipulator slave (ARC, 1985).

The *HSF* Lab has been involved with force-reflecting teleoperation research for more than a decade. Bryfogle (1990) presents algorithms for force-reflecting exoskeletons. Rosenberg (1992) applies virtual fixtures to improve teleoperator performance. Huang (1993) presents equations for *FreFlex* exoskeleton inputs and *Merlin* inverse pose solution, optimized for minimal on-line computation. Repperger (1995) has been very active in force-reflection research, focusing on the operator side of teleoperation.

This paper summarizes force-reflecting teleoperation implementation in the HSF Lab. The system description is first presented, followed by a description of the control architecture, and lastly hardware implementation and future experimentation plans are discussed. Details for the control architecture are presented for the slave manipulator system in (Williams, 1997a), for the force-reflecting master in (Williams, 1997b), and for the Naturally-Transitioning Rate-to-Force Controller (*NTRFC*) in (Williams and Murphy, 1998).

A system similar to the one described in this paper has many potential applications in teleoperation and virtual environments. Specifically, telerobotic systems are considered. The described system gives force/moment feedback to the human operator; this sensory feedback enables more efficient, safe, and realistic operations, even when the remote manipulator is distant from the operator. Potential applications include (but are not limited to) bomb disposal and other hazardous activities, remote maintenance in nuclear power plants, International Space Station maintenance operations, undersea operations, and improved human operator performance. Other applications exist in virtual reality; virtual training and virtual telerobotic simulation can benefit from forces/moments generated and sent to the operator from simulated environments. On a different scale, remote surgery and virtual surgical training applications can benefit from this technology.

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System Description

General System

This paper assumes the following general system characteristics. One or more slave manipulators is to be controlled to accomplish various tasks. The manipulator(s) may be controlled by human operator (teleoperation), autonomously (robotic) or a combination (telerobotic). The slave manipulators should posses at least six degrees-of-freedom (dof) for general spatial tasks. A master device (joystick, hand controller, exoskeleton) with at least six-dof is used for teleoperation inputs. Since Cartesian commands from the master are sent as Cartesian commands to the manipulator(s), the master and slave need not be kinematically similar. Cartesian to Cartesian master/slave control has more capability than joint to joint control. If two slave manipulators are working independently, two master devices may be used. If two slave manipulators are coupled through a common payload, a single master is sufficient. Figure 1 shows coordinate frame definitions which apply to masters and slaves.

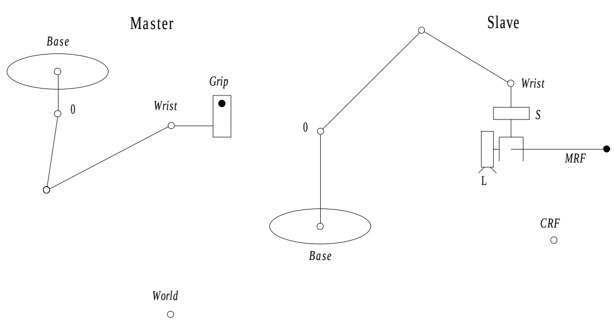

Figure 1. Master and Slave Coordinate Frames

For clarity, dextral *XYZ* Cartesian coordinate frames are represented by dots in Fig. 1. The *World* frame is an inertially-fixed reference frame for all devices. The Master and Slave each have separate *Base*, 0, and *Wrist* frames. The *Base* frame is attached before the first moving joint; 0 is the kinematic base frame; the *Wrist* frame is attached to the last moving link at its joint. The Master and Slave each have coordinate frames attached to each active joint between 0 and *Wrist* (not shown for generality and clarity). The Master *Grip* frame is centered at the human operator's hand grasp point. The Slave has the following frames: *MRF (Moving Reference Frame)* is a user-defined frame which is being controlled. The *MRF* can be placed anywhere as long as it is rigidly attached to the last manipulator link (such as on a grasped payload or even off the physical link). The *CRF (Control Reference Frame)* is a user-defined frame with respect to which the *MRF* is controlled. Cartesian velocities may be commanded in the coordinates of any frame, but all motion relates the *MRF* to the *CRF*. The frames *L* and *S* are the camera lens (for machine vision and/or remote operator views) and force/torque (*F*/*T*) sensor frames; both are rigidly attached to the Slave *Wrist* and *MRF* frames.

The control frames in Fig. 1 are defined for generality. The *CRF* can be moving and the *Base* can also be moving independently with respect to the *World*. The *MRF* can be changed during tasks and is defined to facilitate task completion. (For example, the *MRF* can be the beam node in a beam assembly task. In this case the *CRF* would be the target connecting node location.) The inclusion of the *MRF* and *CRF* is intended to decouple the Cartesian task (including a human operator) from the slave manipulator. Figure 2 shows the general control flow in a force-reflecting teleoperated system (*Pose* stands for Cartesian position and orientation and *Wrench* stands for Cartesian force and moment vector). In this paper a force-reflecting master will be generically referred to as a force-reflecting hand controller (*FRHC*).

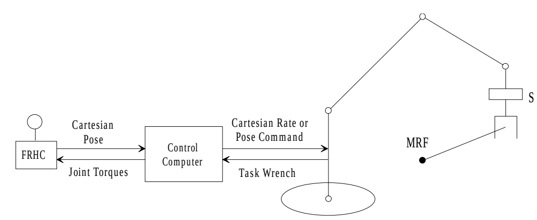

Figure 2. Force-Reflecting Teleoperated System

Specific HSF Hardware

The specific *HSF* Lab hardware is the unique 7-dof *FreFlex* (<u>F</u>orce-<u>*refl*</u>ecting <u>ex</u>oskeleton, Fig. 3) and a 6-dof industrial *Merlin 6500* robot arm, shown in Fig. 4.

Figure 3. FreFlex

Figure 4. Merlin

***FreFlex* and *Merlin* Kinematics**

The telerobotic control architecture presented in this paper requires kinematics transformations which relate Cartesian and joint variables within the master and slave devices. Specifically, this section presents the *DH* parameters, forward kinematics transformation, and Jacobian matrices for the *FreFlex* master and *Merlin* slave.

The kinematic diagrams and *DH* parameters (Craig, 1989) for the *FreFlex* and *Merlin* are given in Figs. 5 and 6, and Tables 1 and 2, respectively. Figures 5 and 6 show the zero-joint-angle configurations (if the angular offsets are included). Nominal values for the *Merlin* lengths are: $a_2 = 17.375$, $d_2 = 11.9$, $d_4 = 17.25$, and nominal values for the *FreFlex* lengths are: $a_3 = 1.969$, $a_4 = -1.969$, $d_3 = 14.64$, $d_4 = 0.625$, $d_5 = 11.77$. All linear units are *inches* and all angular units are *degrees*.

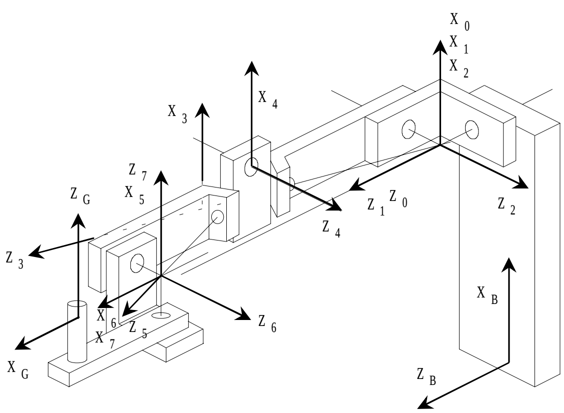

Figure 5. FreFlex Kinematic Diagram

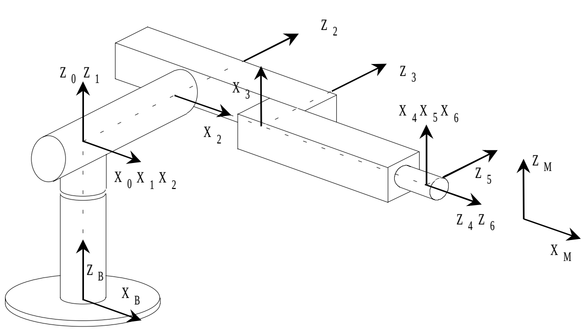

Figure 6. Merlin Kinematic Diagram

Table 1. *FreFlex DH* Parameters

i	α_{i-1}	a_{i-1}	d_i	θ_i	*Limits*
1	0	0	0	θ_1	18,-28
2	90	0	0	θ_2	+130,-52
3	-120	0	d_3	θ_3	±90
4	120	a_3	d_4	θ_4	-3,-166
5	-70	a_4	d_5	θ_5	±90
6	70	0	0	$\theta_6 + 90$	+128,+51
7	90	0	0	θ_7	+57,-52

Table 2. *Merlin DH* Parameters

i	α_{i-1}	a_{i-1}	d_i	θ_i	*Limits*
1	0	0	0	θ_1	±147
2	-90	0	d_2	θ_2	+56,-230
3	0	a_2	0	$\theta_3 - 90$	+56,-230
4	-90	0	d_4	θ_4	±360
5	90	0	0	θ_5	±90
6	-90	0	0	θ_6	±360

The forward kinematics transformation gives the position and orientation (pose) of the moving frame of interest n with respect to the kinematic base frame 0 (Craig, 1989):

$$ {}^{0}_{n}T = \begin{bmatrix} \begin{bmatrix} {}^{0}_{n}R \end{bmatrix} & \left\{ {}^{0}P_n \right\} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} $$

$$ {}^{0}X_n = \{ x \quad y \quad z \quad \gamma \quad \beta \quad \alpha \}^T \quad (1) $$

The pose can be represented by ${}^{0}_{n}T$ (the 4*x*4 homogeneous transformation matrix with the 3*x*3 orientation matrix ${}^{0}_{n}R$ and the 3*x*1 position vector ${}^{0}P_n$) or ${}^{0}X_n$ (whose first 3 components are ${}^{0}P_n$ and second 3 are orientation numbers extracted from ${}^{0}_{n}R$, e.g. *Z-Y-X* Euler convention). Given one row in a *DH* parameter table, the homogeneous transformation matrix relating the pose of neighboring frames in a serial chain is (Craig, 1989):

$$ {}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -d_i s\alpha_{i-1} \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & d_i c\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

where $c\theta_i = \cos(\theta_i)$, $s\theta_i = \sin(\theta_i)$, etc. The forward kinematics transformation for active joints is:

$$ {}^{0}_{n}T = \prod_{i=1}^{n} {}^{i-1}_{i}T = {}^{0}_{1}T\,{}^{1}_{2}T \cdots {}^{n-1}_{n}T \quad (3) $$

The overall forward kinematics for the *FreFlex* and *Merlin* are given below on the left and right, respectively (Note the *FreFlex* and *Merlin* each have distinct *Base*, 0, and *Wrist* frames, see Fig. 1):

$$ {}^{Wo}_{G}T = {}^{Wo}_{B}T\,{}^{B}_{0}T\,{}^{0}_{W}T\,{}^{W}_{G}T \qquad {}^{Wo}_{M}T = {}^{Wo}_{B}T\,{}^{B}_{0}T\,{}^{0}_{W}T\,{}^{W}_{M}T \quad (4) $$

where *M*, *B*, 0, *W*, and *G* stand for the *MRF*, *Base*, 0, *Wrist*, and *Grip* frames. The world frame *Wo* is common.

The Jacobian matrix ${}^{k}J$ for a serial chain maps joint rates $\dot{\Theta} = \{\dot{\theta}_1 \quad \dot{\theta}_2 \quad \cdots \quad \dot{\theta}_n\}^T$ into Cartesian rates ${}^{k}\dot{X} = \{\dot{x} \quad \dot{y} \quad \dot{z} \quad \omega_x \quad \omega_y \quad \omega_z\}^T$ of the frame of interest with respect to the base, expressed in any frame k: ${}^{k}\dot{X} = {}^{k}J\dot{\Theta}$. The i^{th} column of ${}^{k}J$ is the Cartesian velocity of the point of interest due to joint rate *i* alone (with $\dot{\theta}_i$ factored out). This fact leads to the following formula for the i^{th} column of ${}^{k}J$, where ${}^{i}z_i = \{0 \quad 0 \quad 1\}^T$:

$$ {}^{k}J_i = \begin{Bmatrix} {}^{k}_{i}R\left({}^{i}z_i \times {}^{i}P_n\right) \\ {}^{k}_{i}R\,{}^{i}z_i \end{Bmatrix} \quad (5) $$

Equation 5 is applied for each moving joint to yield the 6*x*7 *FreFlex* and 6*x*6 *Merlin* Jacobian matrices, each relating the motion of the respective *Wrist* with respect to *Base*, expressed in **k** (*k* can be different for *Merlin* and *FreFlex* and is chosen as the respective 0 frames in this paper).

Control Architecture

This section summarizes the general real-time force-reflecting telerobotic control architecture. This section briefly presents the slave manipulator control architecture (including an overview of the Naturally-Transitioning Rate-to-Force Controller, *NTRFC*), followed by the force-reflecting master control architecture.

<u>Slave Manipulator Control Architecture</u>

Figure 7 shows the real-time, resolved-rate-based, shared telerobotic control architecture for a single slave manipulator. It is briefly described below.

There are four basic paths in Fig. 7. Starting from the top summing junction, the resolved-rate control algorithm (Whitney, 1969) calculates the commanded joint rates to achieve the total commanded Cartesian rate: $\dot{\Theta}_C = {}^{k}J^{-1}\,{}^{k}\dot{X}_W$ (for more efficiency and better robustness, use Gaussian elimination). These commanded joint rates are then integrated to commanded angles, which are sent to the six independent PID servo controllers for joint angles. Resolved-rate control is appealing because it involves linear equations with a unique solution and multiple input sources can be summed linearly at the input Cartesian rate level. Inverse pose and resolved-rate control are subject to the same singularities. In the neighborhood of singularities, SVD can replace the matrix inverse until the manipulator moves through the singularity.

The path below resolved-rate control is for pose control. The actual pose ${}^{C}_{M}T$ is calculated from joint sensor readings via forward kinematics, and then "subtracted" (algebraic subtraction for position vectors, must use a difference matrix for orientation) from the commanded pose ${}^{C}_{T}T$ to form a Cartesian rate to drive the current pose into the commanded pose.

The wrench (force/moment) loop has two branches. In the upper one, a commanded wrench F_C may be achieved by subtracting the sensed wrench F_M (simple subtraction for both forces and moments) to form a Cartesian rate $\dot{X}_F$ to drive the manipulator to feel the commanded wrench. If F_C is set to zero, this is called force accommodation because the manipulator moves to relieve binding forces/moments of contact. The bottom force branch gives force/moment reflection to the human operator via the force-reflecting master: $\tau_T = J_{HC}^{T}F_W$, where τ_T is the commanded master joint torques, J_{HC} is the master Jacobian matrix, and F_W is the sensed task wrench for the operator to feel.

The pose of the master (force-reflecting exoskeleton) can be used by the operator to input either commanded Cartesian rate $\dot{X}_{HC}$ or commanded Cartesian pose ${}^{C}_{T}T$ for rate- or pose-based teleoperation. Though not shown in Fig. 7, an inverse pose kinematics solution has been adapted from Huang (1993) and implemented to compare the effectiveness of direct pose control vs. the resolved-rate pose control of Fig. 7. For mathematical detail for this manipulator control architecture, see (Williams, 1997a).

The architecture of Fig. 7 allows simultaneous human and automated control of the system on all Cartesian axes; this is called shared control. Any control input may be turned on and off with software switches or enabled only for certain Cartesian axes via the appropriate K_i gain matrix.

Often different control input sources can be in conflict. However, an example of a symbiotic combination of input sources which yields very effective

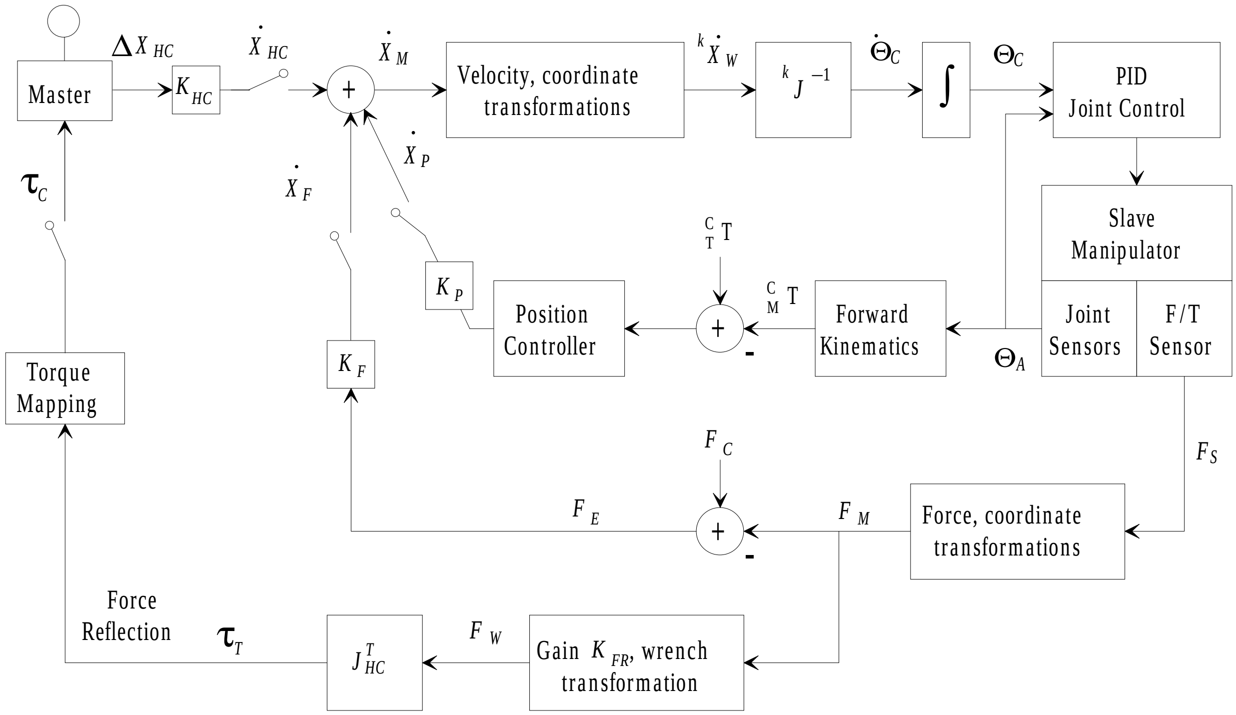

Figure 7. Telerobotic Control Architecture

control in contact is the Naturally-Transitioning Rate-to-Force Controller (*NTRFC*, Williams and Murphy, 1998). Raibert and Craig (1981) present a method for hybrid position/force control where certain Cartesian axes are chosen for position control and the remaining ones for force control. The current system can achieve this by proper placement of zeros in K_P and K_F in Fig. 7. However, excellent free motion to contact characteristics are achieved by combining rate control and force-moment accommodation (*FMA*) on all axes simultaneously. This is the *NTRFC*.

The *NTRFC* is applicable to control of any manipulator(s) with wrist-mounted force/torque sensor, rate inputs, and contact with the environment. The concept was developed heuristically at *NASA* Langley Research Center and demonstrated to be very effective in experiments (Willshire, et.al., 1992). The system behaves as a rate controller in free motion and as a force controller in contact. The transition requires no mode changes, logical switches, or gain changes in the controller software or hardware and thus is termed a natural transition. The transition is a consequence of the physics of manipulator contact with the environment when using rate control with force/moment accommodation (*FMA*). The *NTRFC* concept was extended during summer 1997 at the *HSF* lab by the authors. Rigorous modeling was performed and design procedures were developed (Williams and Murphy, 1998). The *NTRFC* is currently being implemented in the *FreFlex*/*Merlin* system and evaluation experiments are in progress.

Force-Reflecting Exoskeleton Control Architecture

Figure 8 shows the control flow for the implementation of a Cartesian *FRHC* commanding inputs and reflecting wrenches with a telerobotic system in Cartesian space. There is some overlap between Figures 7 and 8; Fig. 8 shows more detail. Figure 8 assumes Cartesian rate inputs; the difference for Cartesian pose inputs is minor.

The center of Fig. 8 shows the operator moving the force-reflecting master (*FRHC*). The difference in the current and reference *FRHC* poses is interpreted as either a 6-dof Cartesian pose or rate input and sent to the slave manipulator. The bottom path in Fig. 8 accomplishes the task wrench feedback to the human operator, as discussed in Fig. 7. In addition, three further *FRHC* algorithms assist the operator in accomplishing tasks: 1) Gravity compensation calculates the configuration-dependent joint torques necessary so the *FRHC* supports its own weight. 2) Return-to-Center force ${}^G F_R$ is used when in rate mode to assist the human operator in finding zero rate input between motions. This area includes constant return-to-center force and virtual walls for axis decoupling (when controlling all 6-dof with one hand). 3) A damping force is included under both rate and pose modes to

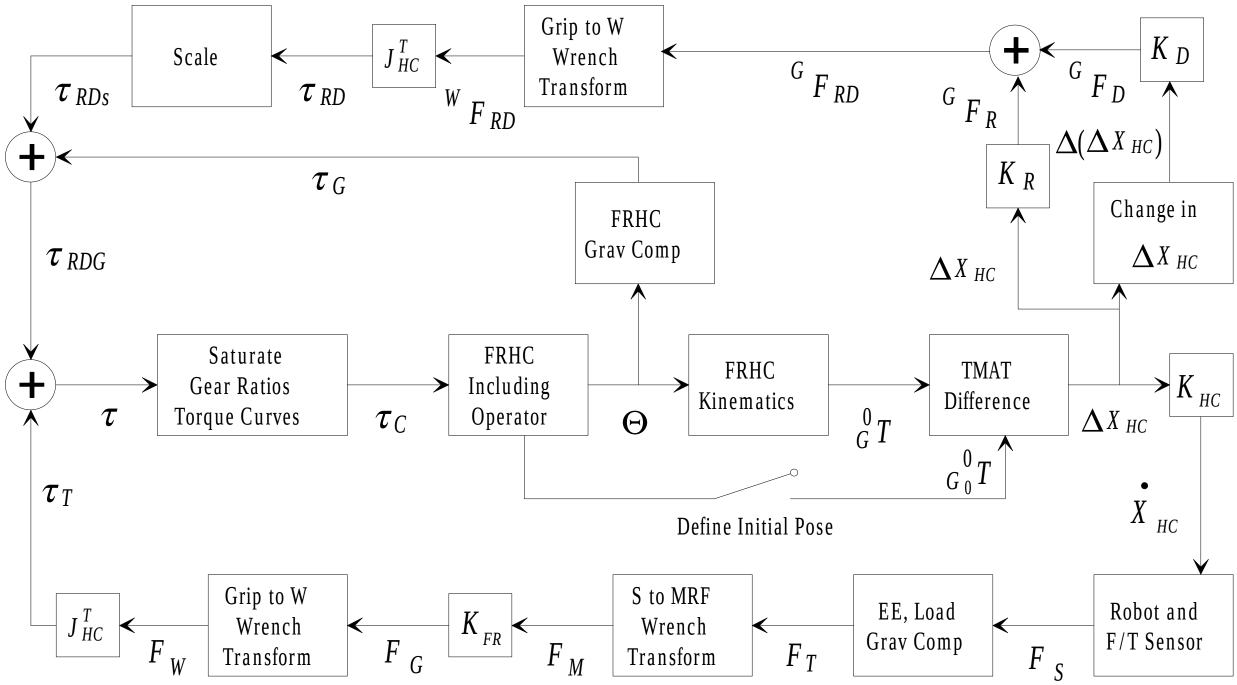

Figure 8. Cartesian FRHC Control Diagram

increase relative stability between the human, remote manipulator, and the environment. The task feedback and these three assist terms are summed at the *FRHC* joint torque level. For mathematical detail in *FRHC* control, see (Williams, 1997b).

Hardware Implementation

A *Matlab* simulation was developed for the *FreFlex*/*Merlin* system with the control architecture of this paper. This simulation is useful to validate algorithms, test new ideas safely, compare data from hardware implementation, and view simulated motions off-line. Joint, pose, and rate control modes are available.

The *Merlin* controller consists of two PC's, the Master CPU and the Servo CPU. The Master CPU runs the AR-Basic interpreter and the Servo CPU is responsible for joint servo control. The High Speed Host Interface allows the user to communicate directly with the Servo CPU via an RS-232 interface. The *Merlin* has a wrist-mounted JR3 force/torque sensor.

The *FreFlex* is driven by seven brushless permanent magnet servomotors which provide high continuous torque and low armature friction and inertia. Bayside gearheads are mounted on each motor. The motors are mounted on an external base minimizing the size, mass, and inertial properties of the *FreFlex* exoskeleton. The exoskeleton has a cable transmission consisting of 19 shafts, 102 pulleys, 92 bearings, and a gear set at the elbow (Odetics, 1992). This cable transmission causes the motion of the *FreFlex* joints to be coupled (Huang, 1993). The *FreFlex* VME chassis contains four VME-based processors and I/0 boards. The VMIC 4100 board outputs voltages to the *FreFlex* motor controllers. The VMIC 2510B board provides discrete input and output channels for the exoskeleton operator interface. An Ironics IV-3230 board is used for force-reflection processing while a second Ironics IV-3230 board is the Master Real-Time Processing Unit. The chassis also contains a JR^3 board that processes information from the JR^3 force/torque sensor mounted at the wrist of the *FreFlex*, a Data Translation DT1401 card that reads the potentiometers, and a Bit 3 card that links the enet and the Sun SPARCstation. Chimera 3.2 (a real-time operating system for reconfigurable sensor-based control systems developed by CMU, Ingimarson, et.al., 1995), loaded on a Sun SPARCstation, acts as the interface between the *FreFlex* and the *Merlin*.

A *FRHC* should have at least three switches. The most prominent should be used as a deadman switch (must be continuously held by the operator to send commands to the robot and receive wrench reflection back). A second switch can be used to define the *FRHC* reference pose as shown in Fig. 8. This same switch may be used as an index button to command the entire slave robot workspace with a limited *FRHC* workspace, when using pose input mode. The third switch can be used to enable/disable wrench reflection from the task to the *FRHC*. The second and third switches do not need to be depressed continuously.

Conclusion

A general control architecture is presented for real-time, sensor-based, rate-based, shared control of general telerobotic systems including force-reflecting hand controllers (*FRHCs*). A *Matlab* simulation of *FreFlex*/*Merlin* teleoperation under joint and Cartesian pose and rate control was developed. This architecture has been implemented in hardware in the HSF Lab at WPAFB. This includes the novel Naturally-Transitioning Rate-to-Force Controller (*NTRFC*). Experiments are planned for 1998 to evaluate pose and rate teleoperation with and without force accommodation and force reflection. A variety of remote real-world and simulated virtual environment applications can benefit from this technology, including remote hazardous operations, remote maintenance, remote surgery, virtual surgical training, and general virtual training. In these applications, the sense of telepresence (for both real and simulated environments) is greatly enhanced through force/moment feedback to the human operator.

Acknowledgements

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