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A 17 Degree of Freedom Anthropomorphic Manipulator

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Abstract

A 17 axis anthropomorphic manipulator, providing coordinated control of two seven degree of freedom arms mounted on a three degree of freedom torso-waist assembly, is presented. This massively redundant telerobot, designated the Robotics Research K/B-2017 Dexterous Manipulator, employs a modular mechanism design with joint-mounted actuators based on brushless motors and harmonic drive gear reducers. Direct joint torque control at the servo level causes these high-output joint drives to behave like direct-drive actuators, facilitating the implementation of an effective impedance control scheme. The redundant, but conservative motion control system models the manipulator as a spring-loaded linkage with viscous damping and rotary inertia at each joint. This approach allows for real time, sensor-driven control of manipulator pose using a hierarchy of competing rules, or objective functions, to avoid unplanned collisions with objects in the workplace, to produce energy-efficient, graceful motion, to increase leverage, to control effective "impedance" at the tool or to "favor" overloaded joints.

1.0 MODULAR SYSTEM CONCEPT

Since forming the company in 1983, we and our colleagues at Robotics Research Corporation have focused our efforts on the design and manufacturing of high-performance modular manipulators and motion controllers for advanced applications in the industrial, space and defense sectors. Our goal is to offer a configurable and open architecture system of mechanical, electronic and software modules that can readily be adapted to suit specific user requirements. The company's commercial line of hardware and software modules is now reasonably extensive, permitting the assembly of a number of novel and promising system configurations.

2.0 SERVOMECHANISM DESIGN

Family of Joint Drive Modules Our current line of robotic servomechanisms, the K-Series and B-Series Dexterous Manipulators, are all assembled from a family of unitized joint drive modules[1]. Each module in this family includes a complete joint actuator and structural system for one degree of freedom. In existing units, individual joint drive modules do not contain the signal conditioning, control and servo power electronics. These components are housed in a control cabinet and connected to the modules with a highly flexible internal wiring harness. Each joint module is designed around a particular size (and thereby torque capacity) harmonic drive reducer and incorporates an electric servomotor with appropriate characteristics. Modules containing identical actuator elements are built in two forms, to serve either as "roll" or "pitch"-type joints. Roll modules effect rotary motions about the axis of the module interface flanges (typically +/-180^{o} or +/-360^{o}), while pitch modules effect rotary motions about an axis perpendicular to the normal vector of the attachment flanges (+/-180^{o}). Modules are joined to each other in manipulator assemblies by quick-disconnect band clamps, secured by a single tangent bolt. An extensive family of different joint module sizes is now in production, permitting the assembly of a wide range of manipulator scales and kinematic configurations, including systems with as few as three and more than 17 degrees of freedom (DOF).

At present, roll and pitch-type modules are available in seven increments of peak torque capacity-- 17,000 lb-in, 8,000 lb-in, 4,500 lb-in, 2,500 lb-in, 1,400 lb-in, 600 lb-in and 150 lb-in, as illustrated in Figure 1. (We will be expanding the family of joint modules in future to include both larger and smaller modules. Joints having as much as 100,000 lb-in peak output torque could be built using Robotics Research's actuator design.) While a variety of three-to-six axis devices might be constructed from the existing module set, only kinematically-redundant units, i.e., ones having seven or more joints, have been manufactured to date.

Manipulator Topologies Three 7 degree of freedom manipulator arm models that have been configured from this set of joint modules are shown in accompanying photographs (Figure 2, below). The K-2107HR is a seven foot long, seven axis manipulator for applications which require a light-weight tool or sensor to be conveyed about a large working envelope with dexterity and speed, and with high repeatability. Operating in a stable temperature state, the K-2107HR has a measuring repeatability at the toolpoint of 5/10,000ths of an inch. The K-1607HP is a five foot long, seven axis unit with a 50 lb. payload configured for general-purpose factory and laboratory use. The K/B-1207 unit is a light-weight (160 lbs.), four foot long, seven-axis arm utilizing brushless motors to achieve a very high payload-to-arm weight ratio.

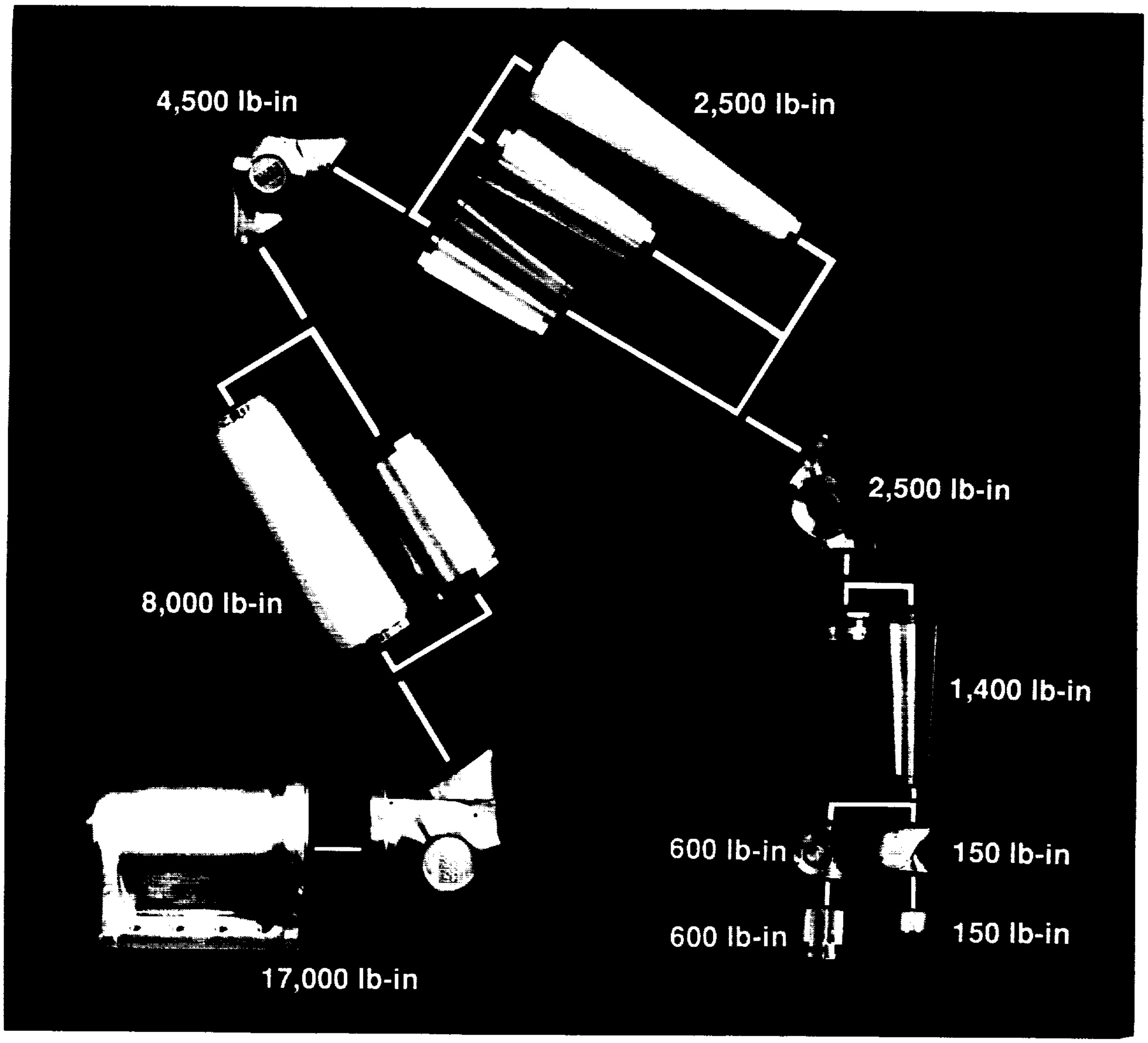

Figure 1:
Family of Joint Modules Currently in Production

In addition to those described above, a variety of alternative serial-chain configurations incorporating more than seven axes could be assembled using our existing joint modules. One example is a nine-axis manipulator arm, created by adding the K/B-1207 wrist roll, wrist pitch and toolplate roll modules on to the first six joints of a K-1607HP arm. An articulated, "snake-like" configuration of this sort might be of use in certain inspection tasks in confined work sites, as in nuclear reactor servicing, where a camera or other light-weight sensor package must be inserted into a narrow space.

Potential manipulator configurations need not be simple serial chains. Indeed, certain branching topologies offer important possibilities. These include the 17-axis configuration that is the subject of this report, and other arrangements, such as those having three or four manipulator arms branching from a common torso-waist link. Such configurations could be constructed and controlled in a similar fashion.

Our 17 DOF model, designated the K/B-2017, has two 7 DOF manipulator arms mounted on and operating in concert with a 3 DOF torso-waist assembly (Figure 3). A natural extension of our modular family, the unit was assembled by affixing two standard K/B-1207 arms onto the end of the first three joints of a standard K-1607.

A branching, 17 degree of freedom kinematic configuration offers several fundamental advantages over a pair of 7-axis manipulator arms of equivalent reach and payload operating from a fixed base. In addition to incorporating more redundancy, which may be used by the sensor-driven controller to mitigate singularities, to avoid obstacles in the workplace and to manage manipulability factors, of particular note is the fact that short tool-handling arms are, by nature, more dexterous and efficient, and less obtrusive and dangerous, than long arms. The 17 DOF configuration employed in this device seems, to the authors, a good compromise. The torso-waist link provides a long overall reach and a large working envelope, while preserving all of the advantages of relatively short, responsive, maneuverable arms for manipulating tools.

Actuator Design The generic actuator design utilized in all K-Series and B-Series modules, including those which comprise the K/B-2017 model, consists of a harmonic drive and a high performance brush-type or brushless samarium-cobalt DC servomotor located on the joint axis, directly coupled to the proximal and distal castings of the module. The flexspline of the harmonic drive is connected to the structure through a metal-to-metal overload clutch and torque transducer. The clutch is generally adjusted to slip at a torque greater than required for full machine performance, but less than would damage the drive or other manipulator components. An independent, high precision instrument gear system, mounted directly on the joint housing, drives a brushless resolver which is utilized to provide joint position and non-quanitized velocity feedback by means of an advanced R-to-D chip. By this arrangement, the servo system has: applied actuator torque, joint velocity and joint position feedback available to control axis behavior. Any or all variables may be commanded or electronically limited by the servo-control system.

Integral Structural System The K-Series module system utilizes an exoskeleton structural approach. The exoskeleton structure provides favorable structural dynamics of the overall manipulator, with low overall weight. It also provides a strong, durable and clean exterior, enclosing all wiring and actuator componentry.

3.0 TORQUE LOOP SERVO-CONTROL SYSTEM

The harmonic drive is unrivaled for compact, light, backlash-free torque multiplication, but its application as a mechanism for directly driving joints in high-performance spatial manipulators is complicated by two factors intrinsic to the device. Besides being relatively compliant, it exhibits a two-per-input-revolution transmission error which excites the inevitable resonance resulting from the inherent reducer compliance. The resonance phenomenon has prevented the widespread application of this otherwise attractive actuator package in robots. K-Series manipulators utilize a servo-control approach which overcomes this problem and has important attributes as regards manipulator control and performance. The conventional approach in robot arms is to control velocity and position of the motor shaft, while assuming that the transmission elements are nearly ideal in their translation of shaft motion into joint motion. The approach taken by two of the authors (Thompson and Eismann) in K-Series servo drives is to treat the motor and harmonic drive as a torque producer[1]. The control feedback parameters are all measured at the interface between proximal and distal joint elements. The joint position commands joint velocity, which commands applied actuator torque. The innermost loop is thus a *torque loop*, capable of bandwidth which

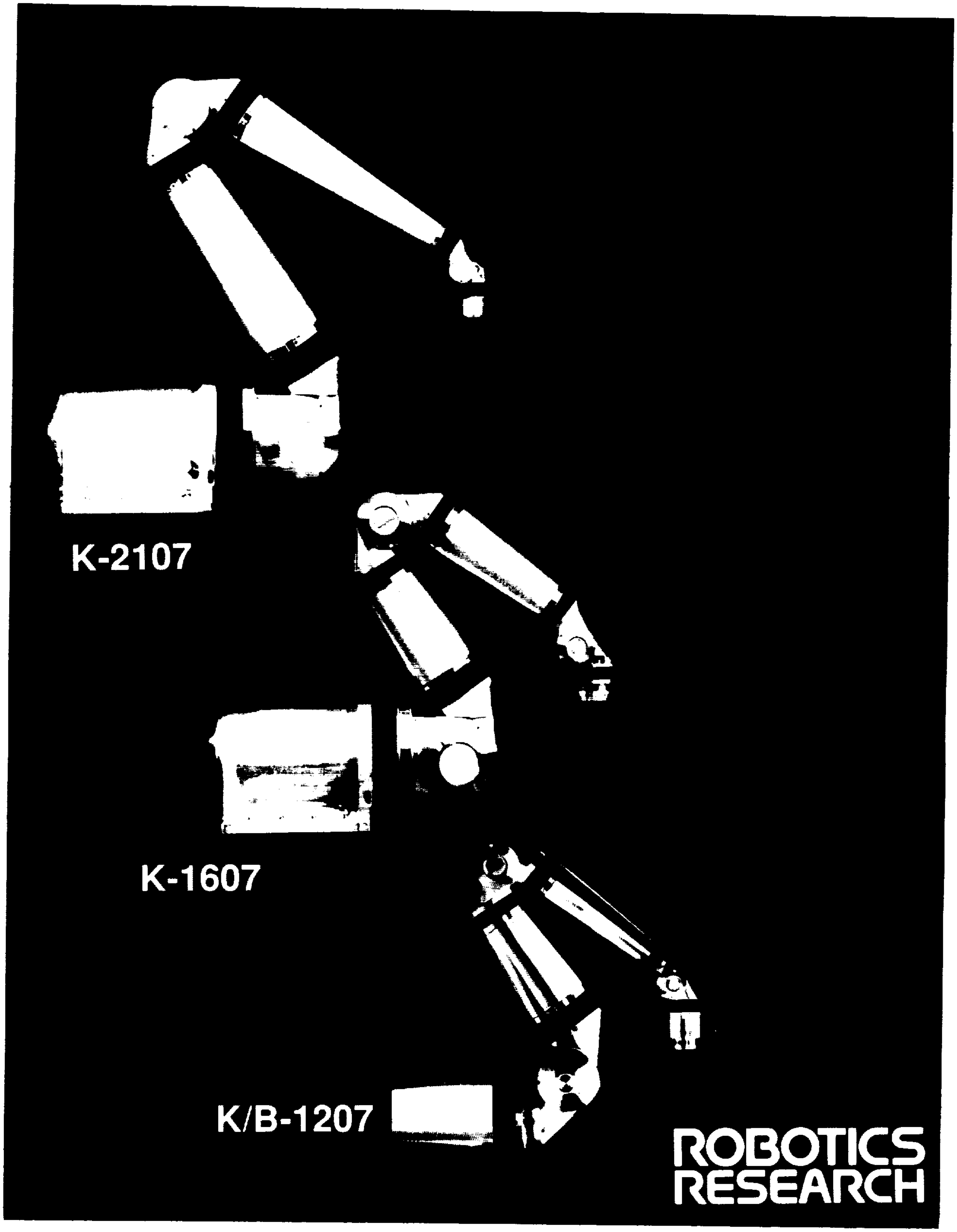

Figure 2:
Configuration of Modules in Three 7 DOF Manipulator Arm Models

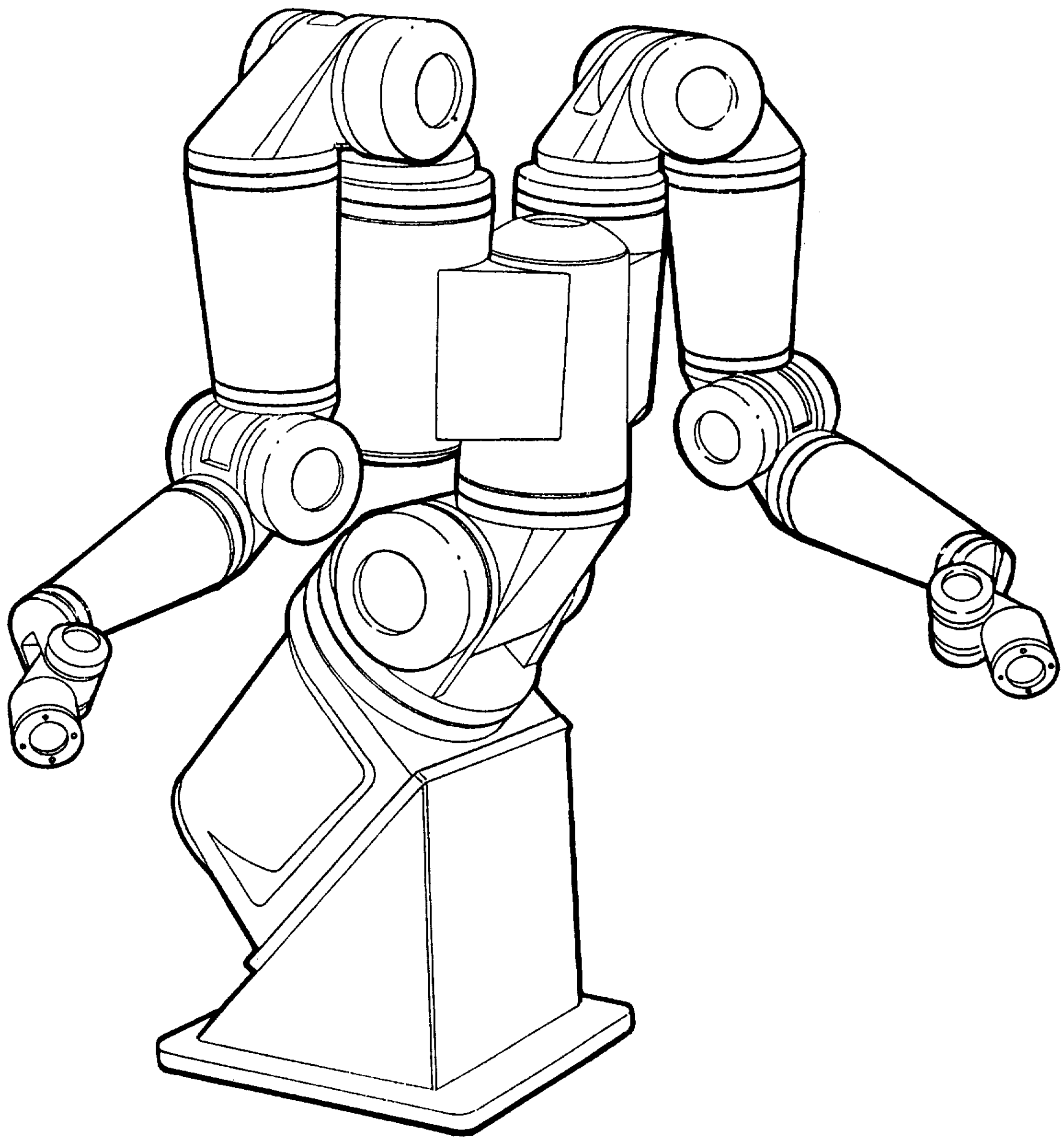

Figure 3:
K/B-2017 Dexterous Manipulator
17 Degrees of Freedom

encompasses the normal resonant frequency range of the actuator package. This torque loop functions to position the motor inertia, however it must, to cause the drive to provide the desired applied joint torque.

As previously mentioned, the torque-loop system provides significant advantages beyond eliminating the harmonic drive resonant response to provide smooth motion. A promising avenue in research on manipulator control is commanding axis torques to achieve high-bandwidth tool force control, or "impedance control"[2]. In K-Series arms, the fastest loop at work in the servo-control system is the torque loop. This innermost loop can remain in operation while mode switching. The torque loop also encompasses and compensates for motor, motor seal and drive friction. Viewed from outside the loop, it imparts to the system many of the attributes of best direct-drive manipulators, while avoiding the relatively poor torque-to-mass ratios of the direct-drive motors.

4.0 MOTION CONTROL SYSTEM

Type 2 Motion Controller The Type 2 Motion Control system configured for the K/B-2017 from our standard hardware and software modules provides an open and modular architecture which enables the user to operate the manipulator in a number of different control modes and at various control levels[1,3]. (Refer to Figure 4.) Like Type 2 Motion Controllers supplied with Robotics Research's 7 DOF arms, this 80386/80387-based hierarchical control system is structured following principles set forth in the NASREM architecture, developed by Dr. James S. Albus, et al, at the National Institute of Standards and Technology (formerly National Bureau of Standards)[4]. The Type 2 system handles trajectory control, inverse kinematics and servo-control functions for the manipulator. The trajectory level accepts Cartesian toolpoint commands from the user's host for each manipulator arm and moves each tool centerpoint from its current to its commanded positions. The kinematics level executes Cartesian-to-joint and joint-to-Cartesian transformations for the 17 DOF system on a 50 millisecond basis. The servo-control level accepts position, velocity, torque or current commands for each joint in the manipulator, interchangeably and independent of the mode of other joints, and closes all 17 servoloops on a 5 millisecond basis. A bus-to-bus interface is provided for high-speed host communications.

For this 17 DOF configuration, the Type 2 provides means to control the orientation of the elbow of each manipulator arm, independent of toolpoint position and orientation, using "Elbow-orbit" commands (Figure 5), as well as means to control torso posture using "Torso-orbit" commands (Figure 6). All joints in the manipulator arms and torso-waist assembly are coordinated and continuously participate in a move, i.e., a commanded motion at the toolpoint of either arm causes all 17 axes to move appropriately under the redundancy criteria which are in effect. In addition, the system can be controlled in any desired topological degeneration of its initial 17-axis geometry.

Control Philosophy Investigators at Robotics Research Corporation believe that complex robotic systems will increasingly utilize the standardized NASREM hierarchical control architecture, in which each successively higher level has a broader purview with respect to space and time, and is equipped with sensory feedback, memory and logical functions appropriate to its level of responsibility. In this context, authority over how to use the kinematic redundancy in the manipulator will not reside within any single level of the control system, but will be affected by decisions made at all levels.

Robotics Research is principally concerned with those levels of the robot control system responsible for making "reflexive motion control" decisions based on local, kinesthetic sensors mounted on the manipulator. These might be viewed as "brainstem" functions, analogous to the autonomic or sympathetic divisions of the central nervous system in biological models. (They are encompassed by Levels 1, 2 and 3 in the NASREM model-- "Servo", "Primitive", and "Elemental Move".)

The reflexive motion control approach developed by Robotics Research has been designed to accommodate the simultaneous operation of a wide range of potential redundancy criteria, including--

1. Reflexive Collision Avoidance
2. Joint Travel Limit Avoidance
3. Impedance Control
4. Torque Management and Redistribution
5. Velocity Management and Redistribution
6. Pose Optimization
7. Mechanical Advantage and Positioning Resolution Management
8. Suspension Emulation
9. Graceful Degradation of Kinematics

A basic strategy is to ensure that the system remains sufficiently redundant to satisfy all of the objective functions in force. A hierarchy of competing rules, or objective functions, can then be defined to make a balanced decision at each clock cycle about how best to dispose manipulator redundancy. We propose that, in general, the robot should attempt to execute the commanded toolpoint trajectory,

1. while avoiding collisions with itself, and
2. while avoiding collisions with objects that are detected in the robot's working envelope, and
3. while recognizing singularities intrinsic to its mechanical geometry and using them appropriately,

a) to produce energy-efficient, graceful motion, or
b) to increase leverage (mechanical advantage), or
c) to control "impedance" at the toolpoint, and

4. while "favoring" joints whose actuators are sensed to be closer to their thermal limits than others.

Obviously, while a higher level in the hierarchical control system may elect to override or reprioritize these objectives based on its broader view of the situation, in normal operation, no one criterion is ever permitted to monopolize the available redundancy. Competing functions coexist. An exceptionally computationally-efficient generalized inverse solver for the Jacobian of redundant systems, devised by one of the authors (Vold), provides means to reduce to practice such a philosophy, even for massively-redundant manipulator configurations.

Robotics Research's Paradigm for Redundant Motion Control The manipulator is construed in our control mathematics as a mechanism where, to each joint, there is associated a spring value with specified stiffness and origin, a viscous damper value, and an inertia value. To each link there is a center of gravity, a mass value, and an inertia tensor. Robotics Research's Spring-Mass-Damper (SMD) model is not a simulation-- dynamic linkage parameters are chosen to provide desirable manipulator behavior, but do not correspond to its actual physical properties.

Motion is accomplished by prescribing incremental Cartesian motion at the end-effector(s), and imposing dynamic joint loads generated by the damping and inertia factors. Additional joint loads may be superposed to accomplish subgoals. Motion may be biased by modifying spring origins. Joint increments are found which are compatible with the instantaneous Jacobian matrix of the system. Using Robotics Research's proprietary algorithm, the solution time for the 17 DOF manipulator shown herein is less than 50 milliseconds operating in C code on a single 20 mHz Intel 80386 cpu with a 80387 coprocessor. Optionally, a basis for the 5 dimensional nullspace of the Jacobian is also computed. The form of our procedures is inherently amenable to parallel processing architectures when higher update rates are required.

Joint position commands are generated that tend to be compatible with the real actuator's capabilities by employing a mass and inertia distribution that approximates the physical system. One may view the inclusion of damping and inertia factors in this model as providing tunable low-pass filters for the actuator velocities and torques. The specified masses and inertias need not, however, be exact. Indeed, by setting those values to zero, a quasi-static solution is generated which is quite satisfactory for slow speed motion.

Reflexive Collision Avoidance Sensory-interactive collision avoidance for redundant systems is implemented by associating with each point obstacle a repellent Cartesian force field [5]. Integrating this force field results in a torque load per joint that tends to push the manipulator away from the obstacle. Multiple force fields are superposed in a linear fashion. Joint limits are avoided by applying counteracting torque loads applied to each axis as it approaches its end-of-travel.

Suspension Emulation During abrupt end-effector maneuvers, peak actuator torque requirements may be reduced substantially by dissipating the manipulator's kinetic energy over longer periods of time. This is implemented by using realistic mass and inertia distributions in the motion control model. In effect, the end-effectors behave like the only unsprung masses in the system.

Impedance Control Impedance control is effected by specifying desired end-effector impedance, position and velocity. As previously discussed, the joint actuators in this 17 DOF manipulator utilize torque loops at the servo level which provide many of the beneficial characteristics of direct-drive motors; in this context, a reasonably simple scheme can be employed to implement impedance control.

The specification of desired end-effector position and velocity translates into an equivalent desired position and velocity in joint space. The specification of end-effector stiffnesses translates directly into joint space by forming the congruent transform of the Cartesian stiffness matrix with the Jacobian of the kinematic transformations. In a redundant manipulator, this joint space stiffness suffers a rank loss equal to the redundancy of the manipulator, such that to the Jacobian must be adjoined a basis for the null space. A specification of impedance for orbit moves, such as torso pitch and shoulder pitch, is implicit.

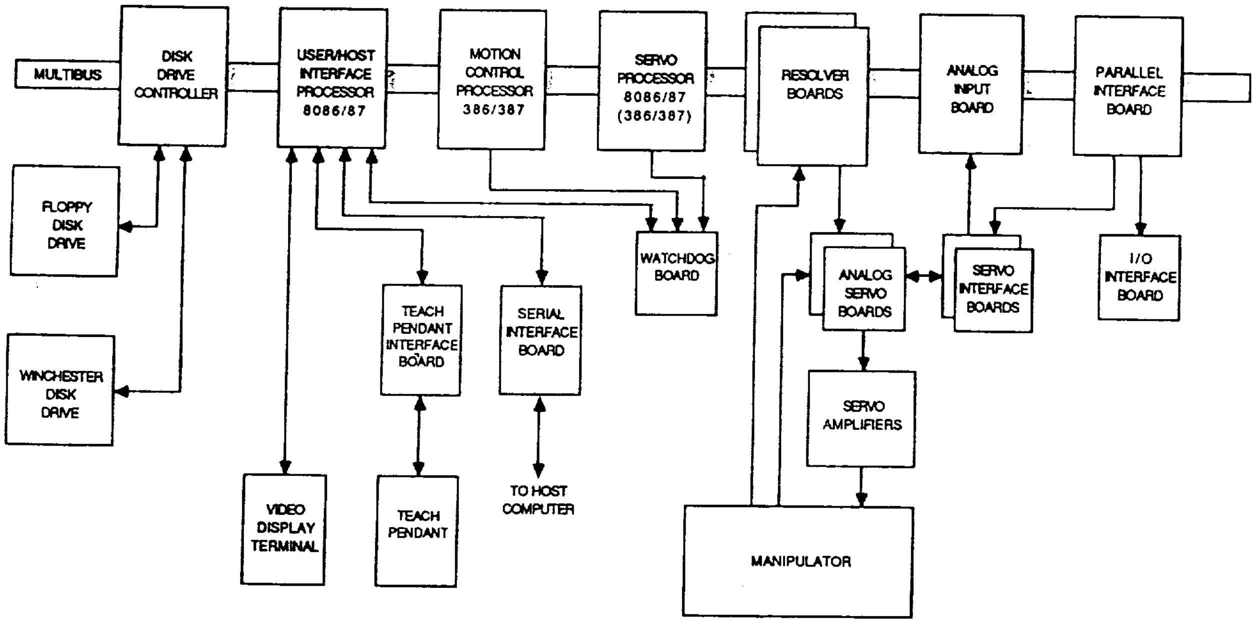

Figure 4:
Type 2 Motion Controller
Hardware Architecture

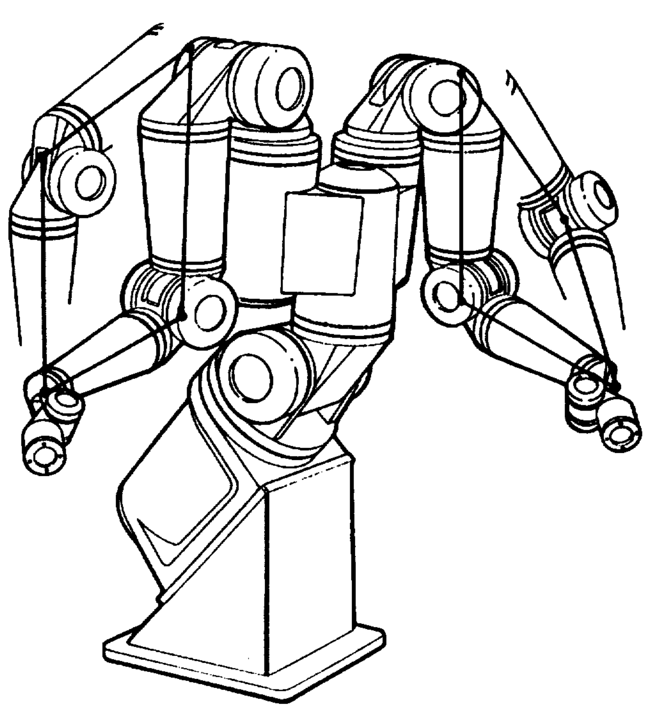

Figure 5:
Elbow "Orbit" Moves
with 17 DOF Manipulator

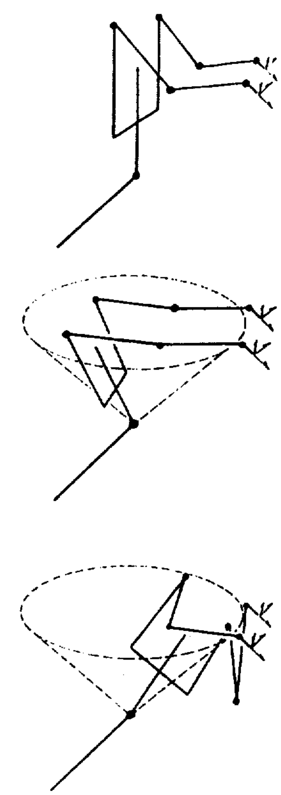

Figure 6:
Torso "Orbit" Moves
with 17 DOF Manipulator

Mechanical Advantage and Positioning Resolution Management In conventional manipulators, singular positions announce their presence by demanding high joint velocities to achieve small end-effector motions. While a near-singular position is not usually desirable, the end-effector enjoys considerable mechanical advantage at that instant. Also, precision of motion at the end-effector is greatly increased.

In a redundant manipulator controlled according to our Spring-Mass-Damper (SMD) model, the emulation of nature tends to mitigate excessive velocities and torques, such that singular regions in joint space are avoided. However, in order to achieve required precision for fine manipulation, or sufficient leverage for a high-force task, a redundant manipulator can be made to seek out near-singular poses using this technique while maintaining sufficient redundancy to break singular deadlocks.

Torque Management and Redistribution Torque management enables the manipulator to carry out its tasks, while controlling torques, velocities and power within safe limits and with economy. Higher level control functions may preselect desirable poses, while, at the reflexive motion control level, torque management is implemented through judicious selection of spring stiffnesses, damping and inertias in the SMD model. Favoring overloaded or temporarily "over-worked" joints is an example of torque management.

Pose Optimization Pose control allows the redundant manipulator to be configured for specific task objectives. Pose is normally thought of as a quasi-static configuration in joint space, but in our control philosophy, pose also includes velocity, such that the inertia in the manipulator can be exploited.

Pose is normally based upon experience or task planning, but may also be determined on-the-fly by the reflexive motion control level tracking the inertia distribution and second-order properties of the kinematic transformations. Pose is implemented by biasing the spring origins in the conceptual control model.

5.0 CONCLUSIONS

The 17 degree of freedom K/B-2017 Dexterous Manipulator and Type 2 Motion Controller described herein, assembled using standard hardware and software modules, represents a natural extension of Robotics Research's modular manipulator series. It is one of a number of new kinematic configurations for manipulators that can be practically implemented using these proven components.

The anthropomorphic branching topology used in this system appears to the authors to be a good solution to the problem of achieving long reach and a large working envelope, without sacrificing the intrinsic advantages of compact, highly dexterous tool-handling arms.

An exceptionally wide range of postures can be assumed by this massively redundant system and a variety of competing objective functions can be satisfied simultaneously. Posture control functions such as reflexive obstacle avoidance and the favoring of overloaded joints, of nominal utility in seven-axis arms, can be demonstrated in a 17 degree of freedom device to have great benefit for overall manipulation capability, reliability and task performance.

We believe this highly anthropomorphic device promises to be an ideal testbed for research in "man-equivalent" telerobots for space servicing, nuclear servicing and defense applications.

6.0 REFERENCES

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