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Advanced Development for Space Robotics with Emphasis on Fault Tolerance

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ABSTRACT

This paper describes the ongoing work in fault tolerance at the University of Texas at Austin. The paper describes the technical goals the group is striving to achieve and includes a brief description of the individual projects focusing on fault tolerance. The ultimate goal is to develop and test technology applicable to all future missions of NASA (lunar base, Mars exploration, planetary surveillance, space station, etc.).

INTRODUCTION

The University of Texas at Austin, in concert with the Robotics Division at JSC and funding support by the telerobotics program at NASA headquarters, has undertaken a long term effort to establish advanced component and system technology for space robotics with emphasis on fault tolerance [Butler et al.][Tesar '89][Tesar et al.]. The goal is to develop and test technology applicable to all future missions of NASA (lunar base, Mars exploration, planetary surveillance, space station, etc.). This technology would be in balance with the astronaut sharing tasks based on performance, cost, and availability issues. In order to reduce costs, the system would be made up of a finite number of modules (both hardware and software) proven by extensive testing in space. This set of modules would be constantly under technical development so that "tech mods" would be feasible at any time. Also, the repair and logistics functions (warehousing of spares in space) would be based on these modules to further reduce costs. This architecture would allow the specification of a robot configuration "on demand" reducing the threat of obsolescence and freeing the mission planner to aggressively use advanced (yet proven) technology.

The following is an overview of the structure of the program at The University of Texas at Austin.

1. **Actuator Technology** — Present actuator technology is largely unchanged since 1965 except for the utilization of rare earth motors and improved electronic controllers. The goal is to aggressively develop component technology which can be integrated in a carefully designed class of actuator modules made up of dual motors, brakes, gear drives, clutches, sensors, electronic controllers, etc., which would provide fault tolerance for dramatically improved performance and reliability of space mechanisms including robotics.

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2. Modular Architecture — A true modular architecture (in the same form as has proven useful for computer systems) can not only reduce life cycle costs (repair, tech mods, logistics spares planning, etc.) but can dramatically increase performance while unfettering the designer to more freely and quickly develop actual operating systems to satisfy future space missions. It is proposed to assemble and reconfigure a broad population of systems from a very small collection of proven and optimized modules produced at lower costs.

3. Task Planning — The complex motion of a body in space to trace out precision trajectories requires the sophisticated theory of algebraic curves to smoothly coordinate all 6 DOF of the end-effectors. The need for dependable task planning derives from a spectrum of demanding physical tasks such as debris damage inspection, precision wiring disassembly and assembly, force fit assembly, dual arm operations, etc. while avoiding obstacles. The goal would be to make task planning more automated requiring primarily supervisory involvement by the astronaut - reducing their time burden and potential fatigue.

4. Dual Arm Operations — Due to the lack of frictional stability generated by gravity forces, all parts must be under control at all times to prevent "dropping". This means that either special fixtures (the bane of data base control in manufacturing) must be employed or dual arms must perform the relative motion tasks (force fit assembly, control of ungainly objects that may be easily damaged, removal of insulation wrappings, bending to fit, etc.) that are sure to occur on long duration missions. No real time operation of a dual arm system capable of these tasks exists today. For two manipulators of 7 DOF each, this requires a level of control (precision force and position of 14 inputs to control 6 relative outputs) far beyond any standard approaches (PID, fuzzy logic, sliding mode control, adaptive control, etc.).

5. Task Performance — Long duration space missions suggest an enormous range of physical tasks of great complexity (handling of large modules, precision welding and forming, unstructured tasks associated with joining and fastening, precision machining, etc.). This complexity can be met only by a criteria based decision control structure based on accurate system parameters (using careful metrology) and hundreds of performance criteria. A prioritized selection of these criteria will be used to create performance indexes to compare the model based performance with the actual performance derived from a very broad collection of sensor signals. Differences between actual and modeled performance will be the basis for adjusting the control inputs to the system.

6. Condition Based Maintenance — Having established a model reference control structure comparing actual with predicted performance, it becomes feasible to monitor the system over time to determine when basic maintenance (replacement of actuator components, sensors, controllers, etc.) should be performed and to provide an archival record of that performance. This should improve the system's reliability, reduce the cost of operation, prevent unexpected failures, and provide lesson's learned for the operator and the designer of future components as well as to the mission planner for module selection to make up systems for other tasks.

7. **Fault Tolerance** — Fault tolerance is virtually non-existent in present robotics development for space. A full architecture for fault tolerance involves four levels (alternate physical pathways) of mechanical structure to avoid faults. The UT program strongly recommends a 10 DOF manipulator system (level III) made up of dual actuators (level I).. This level of choice (20 actuator inputs to control 6 outputs) can only be achieved by a criteria based decision making structure based on performance indexes composed of hundreds of physical criteria (which demands an extremely high computational capacity). Such superior system controller technology (several gigaflops) is emerging as a commodity (at reasonable cost) in the near term. Hence, fault tolerance is not only feasible but it can only be achieved through a comparative analysis between an accurate and complete analytical model reference and a sensor based actual model of the system. This makes Fault Detection and Isolation (FDI) possible. No other method of control does.

8. **Man-Machine Interface** — Because of the extraordinary value associated with the time of the astronaut, the interface between man and machine is being recognized as a key resource to maximize overall performance and to train (skill) the system's operator. Very complex operations (dual arms, disturbance rejection, unstructured tasks, precision assembly at small scales, multiple slaves, obstacle avoidance, etc.) require an exceptional level of dexterity and task performance. This is best achieved by setting operational priorities (selection of criteria, performance indexes, threshold levels for fault identification, etc.) by human intervention. Specially designed actuators, human augmentation software, fault tolerance, etc., must be built into future manual controllers to maximize the task performance of an increasingly complex slave manipulator technology.

9. **Ground Based Control** — As space missions develop (by analog, with the aircraft pilot), the astronaut will be less available to perform mundane, repetitive, and low valued tasks. In order to reduce costs, the demand on the astronaut's time, and to reduce risks, the robot will either have to be operated remotely from a protected module or it will have to be operated from a stand-off position (say the moon or from a control center on earth). This set of conditions leads to the inevitable conclusion that an enhanced man-machine interface to remotely control an array of deployed slave manipulators (robots) in space is essential.

10. **Augment RRC Technology** — The Robotics Research Corporation has produced a sophisticated modular manipulator of high smoothness and resolution which is widely used in NASA laboratories as a demonstrator. The AARMS facility at JSC is made up of two 7 DOF RRC arms on two separate precision 2 DOF pedestals to make up a valuable demonstrator of the technology for space station operations. A 17 DOF system (two 7 DOF arms and a 3 DOF torso by RRC) has been made available by Grumman Corporation to The University of Texas at Austin. Both of these systems will be used to integrate and evaluate much of the technology described in this paper. The goal is to test the most advanced control

software for performance, condition based maintenance, and fault tolerance in real time (say 10 milli-sec.) and to do so with improved operator intervention.

Overall, the program at The University of Texas is concentrating on two levels: the actuator as the driver of the system (equivalent to the computer chip as the driver of computers) and at the system performance level (equivalent to the operating system in personal computers). The objective is to make these two technologies standards for the field of intelligent machines and robotics. This universality is what has created the value in personal computers: increased performance at lower costs. In addition, the program is laying the foundation of a revolutionary approach to control the complex, coupled, and highly nonlinear structures involved, to show the continuum from task performance, condition based maintenance, to fault tolerance all of which depend on a computationally based model reference compared to a sensor identified model. This continuum now becomes unified because of the availability as a commodity of a low cost system controller of several gigaflops.

The central part of this paper will outline on-going development activity at The University of Texas at Austin to meet these 10 technical objectives. The final section of the paper will provide a projection of further development where not only will space requirements be addressed, but also aggressive implementation for industrial technology (manufacturing) will benefit from this investment by NASA.

ARCHITECTURES

The level of performance and versatility expected from space robots makes it imperative that particular emphasis be placed on the question of architecture across multiple domains. While such design issues have to be addressed for each of those domains (mechanical, electronic, and software), certain essential principles may be allowed to pervade the system's architectural considerations. These principles are 1) modularity and 2) redundancy.

Traditionally, mechanical systems have had monolithic architectures that do not permit easy repair and replacement, nor the fluent incorporation of advances in component technologies. Ease of repair and replacement are directly linked to the *availability* of the system and is, therefore, a matter of immediate concern to space systems. The deficiencies of such a philosophy, or lack of one, are best offset by aiming for an architecture that is highly structured and modular. A true modular architecture helps reduce life cycle costs and frees the designer to quickly prototype and develop actual operational systems for future space missions. The UT program has been concerned with the development of modular structures for space robotics, across the domains of mechanisms, electronics and software.

Redundancy is demanded by twin operational considerations for space operations: safe and enhanced performance provided by redundant systems--to be explained in a later section--and the ability to tolerate faults. *Fault tolerance* in a robotics context may be defined * as the capability of the system to sustain a failure and still continue operation

* due to C. Price [Tesar et al.]

without significant impact on the manipulator payload or its immediate environment. Graceful degradation is often inadequate as a requirement and uncontrolled motion must at all costs be minimized. Fault tolerance is assured by the incorporation of protective redundancies and their organization into an effective and responsive architecture. While the causes of unreliability do not disappear, their effects are counteracted by the capability of the system to be intelligent, and to mask the failure or reconfigure itself in the event of component failure. It must be emphasized that these redundancies are *active redundancies* that are operational at all times and which enhance the performance of the robot through the optimization of secondary criteria. We now consider general modular manipulator architectures for fault tolerance.

The Four-level Architecture

The conceptual outline of a total architecture based on modularity principles has been presented in [Butler et al.]. While the issue of architecture depends ultimately on the context and specific tasks envisaged of the robot, it is possible to devise a broad architectural scheme that is based on the requirement [Chladek] that the system be two-fault tolerant. The resulting architecture, in its most general form, is capable of providing a masking redundancy at the first level and a dynamic or reconfiguring redundancy to tolerate the second fault. The organization of these redundancies may be conceived in four levels and they constitute a subsumptive architecture [Sreevijayan]. The four levels are:

1) extra actuators per joint (e.g., prime mover duality)
2) extra joints per DOF (redundantly actuated parallel structures, e.g., 4-legged spherical shoulder)
3) extra DOF per arm (redundant manipulators)
4) extra arms per manipulator system (e.g., dual arm robots, four-fingered hands, etc.)

We now discuss specific prototypes being developed at the University of Texas at Austin that will provide component technologies for realizing modular and redundant space manipulators.

2-DOF Redundant Knuckle Mechanism

The knuckle, shown in Figure 1., can operate either as a force feedback joystick or as a 2 Degree-Of-Freedom (DOF) manipulator. The knuckle demonstrates modularity and Level I fault tolerance at the servo level. It uses two independent servo systems per single DOF to obtain Level I mechanical redundancy. Modularity is demonstrated in the servo control hierarchy (see description of DISCs). The system is designed to handle a minimum of 1 fault before failing. The system controller acts as a supervisor in analyzing the sensory feedback with a Fault A servo system can either remove itself from the system or be removed from the control hierarchy by its parallel controller. Each servo system consists of a clutch, a brushless resolver, a brake, a Hall-effect sensor and a three-phase Brushless DC motor The system controller consists of a 486 PC operating under the Lynx O/S® real-time operating system. The system controller communicates to the servo controllers via a HDLC medium at a rate of 1 MBit/s. HDLC is a communications protocol based on IEEE RS-532 standard.

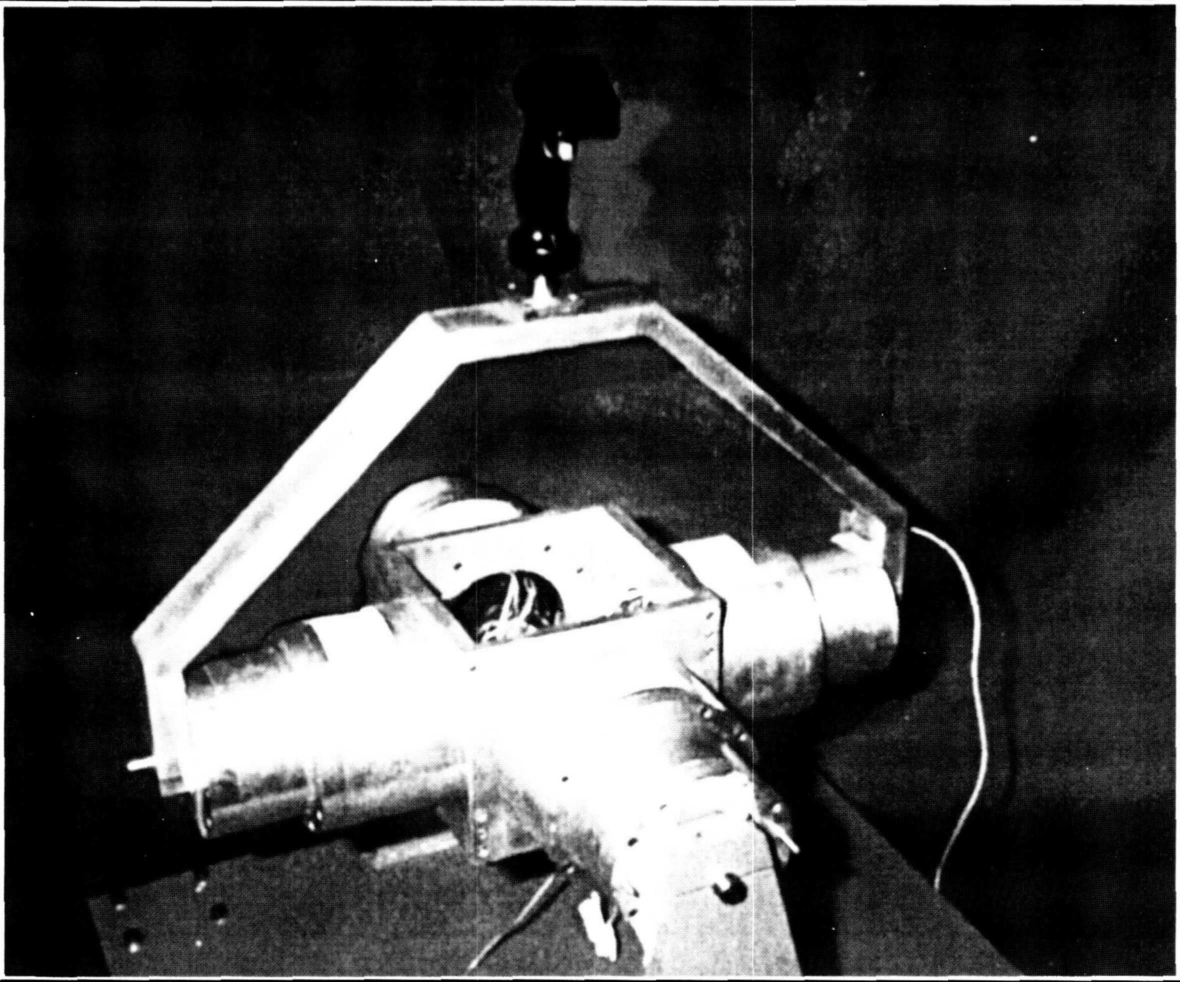

Figure 1. The fault tolerant knuckle.

Modular Brakes for the Fault-Tolerant Actuator

A new brake was developed for use in the next generation of robot actuator technology. The caliper disk brake has an annular geometry that capitalizes on the structural integrity of the robot actuator shell. One to four independent brake calipers can be positioned around the rim of the disk to give a redundant capability. The torque path goes directly from the calipers to the actuator shell to produce a truly, lightweight, integrated design. An ultra-low power consumption is achieved since only a very small current is required to hold the brake pads in the released position. The brake design is very compact, lightweight and has a high torque/weight ratio. Performance parameters were determined from prototype testing and compared to a set of average performance parameters derived from a database of commercially available high performance brake modules. The new brake design has achieved a number of improvements when compared to standard practice.

Criteria	Benefit
Torque/weight Ratio	3X Better
Compactness	2X Better
Response Time	2X Faster
Operating Power Consumption	700X Better

Table 1. Benefits Of The Improved Modular Robot Brake

The Digital Intelligent Servo Controller (DISC)

The Robotics Research Group has developed a Digital Intelligent Servo Controller (DISC), shown in Figure 2., that expands the actuator controller technology. The DISC is a very compact brushless DC servo controller that offers numerous features not contained in any single commercial system available today. Some of the features include: multiple sensor interfacing, compact 'smart' power electronics, fault tolerance, and high speed digital communications designed in a modular package.

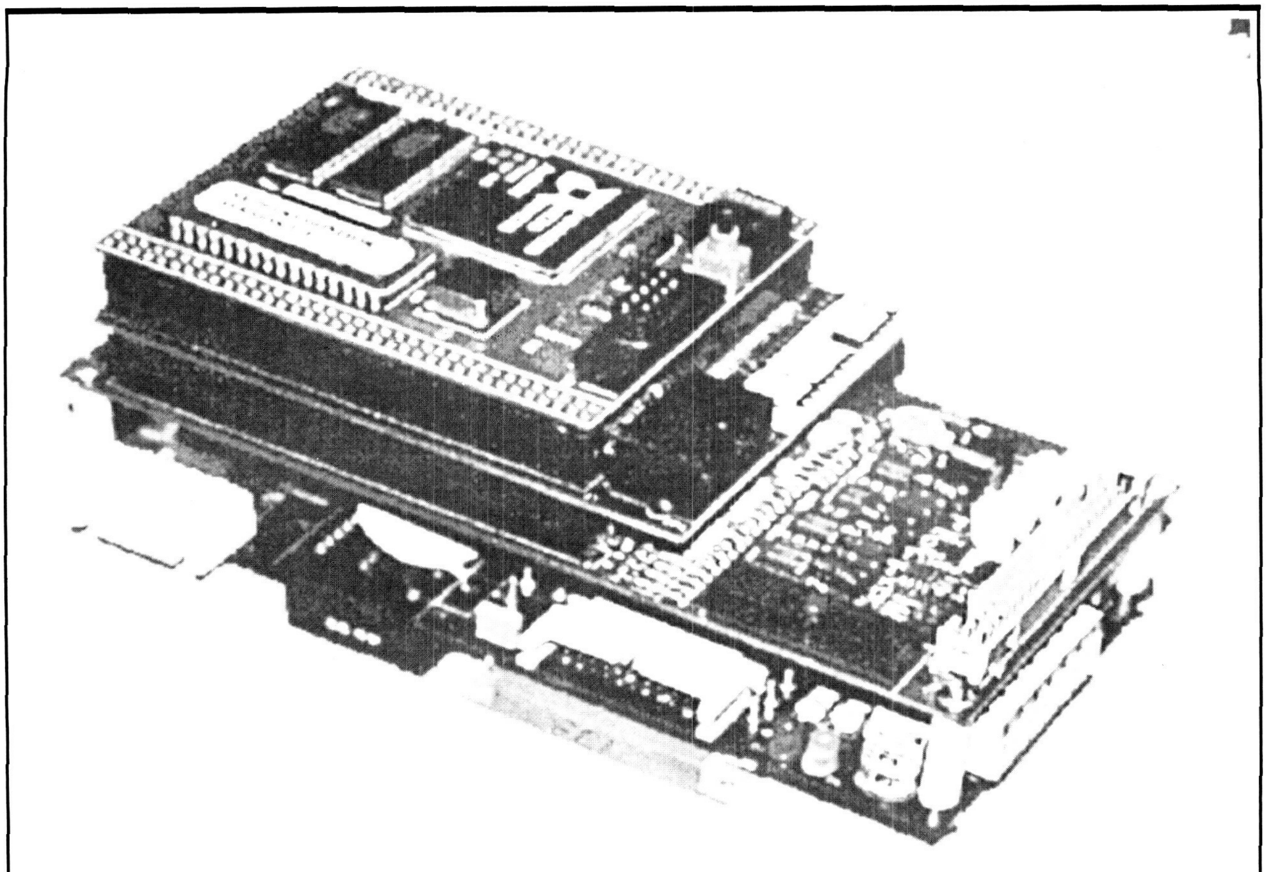

Figure 2. This DISC fault-tolerant electronic controller.

Object-Oriented Software Architectures

The Robotics Research Group at U.T. is in the final phase of designing and developing a unique object-oriented software for advanced robots. This software provides abstractions for various robotic concepts like kinematics, dynamics, decision making, and fault-tolerance. The abstractions are implemented as a part of an inheritance hierarchy. This software is developed in a modular and extensible fashion, with the user having the capability of connecting various modules as desired. This promotes rapid-prototyping. Also, the framework provides for reuse and extensibility. For example, if a generalized inverse kinematics module would not satisfy user needs, the user could easily substitute that module with a custom inverse kinematics module. Such a change does not affect the structure of the rest of the software. This software provides an ideal environment for robotics research and allows for interaction at all levels of abstraction. Moreover, the rapid-prototyping capability of the software allows for easy experimentation. In addition, due to the general nature of this software, it is applicable to a wide variety of robotic structures.

DECISION-MAKING AND CONTROL

A redundant robot is an extremely complex system with essentially limitless options for performing most tasks. The extra resources demand active utilization during normal operation. This refers to the *redundancy management* mode of operation where the control inputs are selected based on the optimization of selected performance criteria. Our position is that no single criteria is sufficient for decision-making and control, but rather that a suite of weighted and ranked criteria must form the basis for any intelligent decision making process. Towards this goal we have conceptualized over 100 different performance criteria and mathematically formulated 30 of these. The section on criteria development describes some of them.

After formulating and prioritizing the performance criteria for a given system, there still remains the problem of incorporating them into a decision making system that will maximize performance while simultaneously satisfying operational constraints. Fault-tolerance places additional demands on the decision maker because the robot may suddenly lose one or more resources, thus requiring a change in control emphasis from one of redundancy management to that of *failure management.* The failure management further breaks into chronological stages. First is fault detection and isolation (FDI). The fault detection routines must continuously monitor the system and upon detection of a fault, must isolate and identify the source of the fault. At this point, the reconfigurable control system responds to the change in the robot's resources and automatically restructures the control algorithm so that the control inputs are reconfigured while at the same time maintaining task performance. Finally, condition-based maintenance on the robot will restore it to full-capability.

Serial Robot with 21 Degrees of Freedom

As an example of redundancy resolution in a fault-tolerant system, consider the inverse kinematics problem for the massively-redundant serial robot with 21 degrees of freedom shown in Figure 3. Though this is clearly a conceptual robot, it represents a system with a tremendous degree of redundancy. We have developed a unique redundancy resolution technique based on the method of sequential filters developed by Eschenbach and Tesar [Eschenbach].

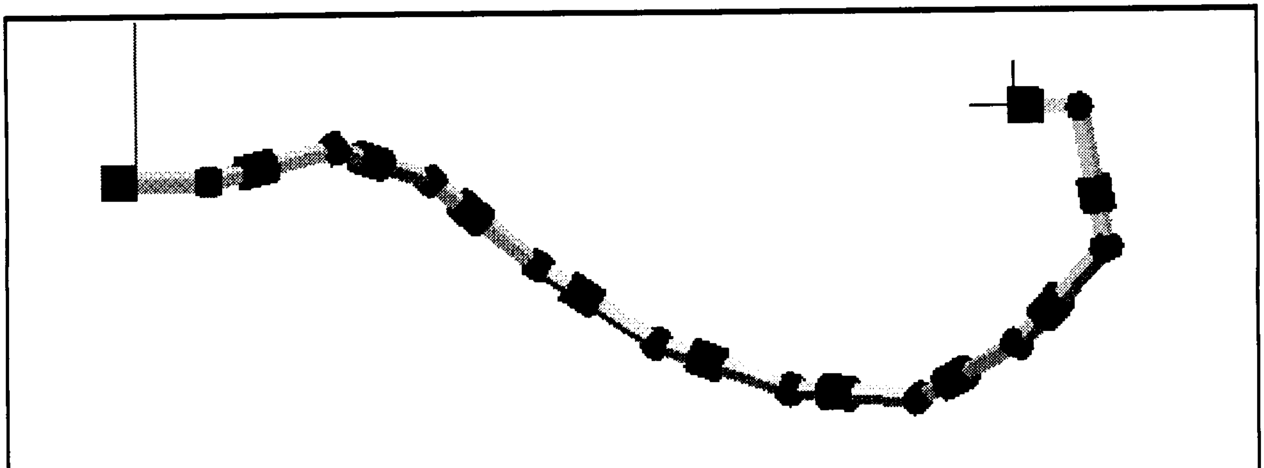

Figure 3. A conceptual robot with 21 degrees of freedom.

This method of redundancy resolution explicitly identifies a set a feasible options for the robot's motion in the next instance using a series of joint-level perturbations. Perturbing the joint displacements a small amount, $\Delta\theta$, from their current values, $\underline{\theta}$, generates a set of local configuration options, $\hat{\underline{\theta}}$: $\hat{\underline{\theta}} = \underline{\theta} + \underline{\varepsilon}\Delta\theta$, where $\underline{\varepsilon}$ is an arbitrary sweep vector with all elements equal to ± 1 or 0. The vector of current displacement values, $\underline{\theta}$, is the base point for the perturbations. At the base point, $\underline{\varepsilon} = \underline{0}$. All other $\underline{\varepsilon}$ with elements equal to combinations of ± 1 and 0 generate points on the faces, edges, and vertices of an n-dimensional hypercube with n equal to the number of degrees of freedom. The sequential filters then evaluate and rank the options based on the performance criteria and operational constraints. The logical sequence first applies the least computationally demanding constraints, and then evaluates the remaining options based on the higher-level performance criteria. The application of equality constraints on the end-effector's placement, followed by travel, speed, and acceleration limits at the joint-level will typically eliminate the vast majority of the options. A fault in one of the joints simply removes the options associated with perturbations of the faulty joint from the feasible set. Using this technique, we can resolve the redundancy of this extremely complex system at hundreds of cycles per second on common personal computers.

Performance Criteria

The ability of a decision making system to control a redundant robot system depends on the quality of the information it is provided to make those decisions. *Performance criteria* are mathematically rigorous metrics which are derived from the kinematic and dynamic robot models Each performance criterion quantifies a characteristic inherent to the operation of the robot and thereby provides vital information concerning its current state.

The decision making system may make use of these criteria to determine the *quality* of various self-motion configurations and select a solution that best achieves the specified goals.

Performance criteria may divided into two categories based on the information they require. *Task dependent* criteria rely on information concerning the current state of the robot's task; such as velocity or force specifications. Conversely, *task independent* measures are defined only from the physical parameters inherent to the robot; geometry, inertia, and compliance for example. While both categories provide useful information, the robotics program has focused on a criteria formulation free of the predetermination of the robot task. This task abstraction will extend the application base to which the criteria may be applied. Performance criteria developed at The University of Texas at Austin's Robotics Group consists of 29 measures, defined in these categories:

- **Geometric**.......... based on first and second order kinematic properties of the manipulator,
- **Inertial**................ based on the inertial terms in the manipulator's dynamic equations,
- **Kinetic Energy**.. based on system level kinetic energy content and individual link contributions
- **Compliance**....... based on the link and joint compliances (stiffnesses) of the manipulator.

A simple, yet very powerful example of a geometric criterion is derived from the First-Order velocity equation which is given as

$$\underline{\dot{u}} = \left[G_\phi^u\right]\underline{\dot{\phi}},$$

where,

- $\underline{\dot{u}}$ is the end-effector velocity,
- $\underline{\dot{\phi}}$ is the joint velocity, and
- $\left[G_\phi^u\right]$ is the manipulator Jacobian.

The *singularity detection criterion* is derived from this mapping of joint to end-effector space as

$$\eta_\sigma = \sigma_{\min}.$$

where, $\sigma_{\min}$ is the minimum singular value of the manipulator Jacobian, and is determined from the *singular value decomposition*..

Level III Fault Tolerance

Figure 4. shows a serial robot with 10 degrees of freedom and fault-tolerance at Levels II and III. This kinematic arrangement affords the robot complete dexterity even if any one of the joints failed and is locked. The manipulator has a regional structure with 6 degrees of freedom (that is built on a regional sub-structure with 3 degrees of freedom) and an orientation structure with 4 degrees of freedom. The use of two-roll joints in the regional structure provides positional fault-tolerance and the 4 DOF orientation structure retains all joint axes intersecting at right angles even if any one of the wrist joints fails.

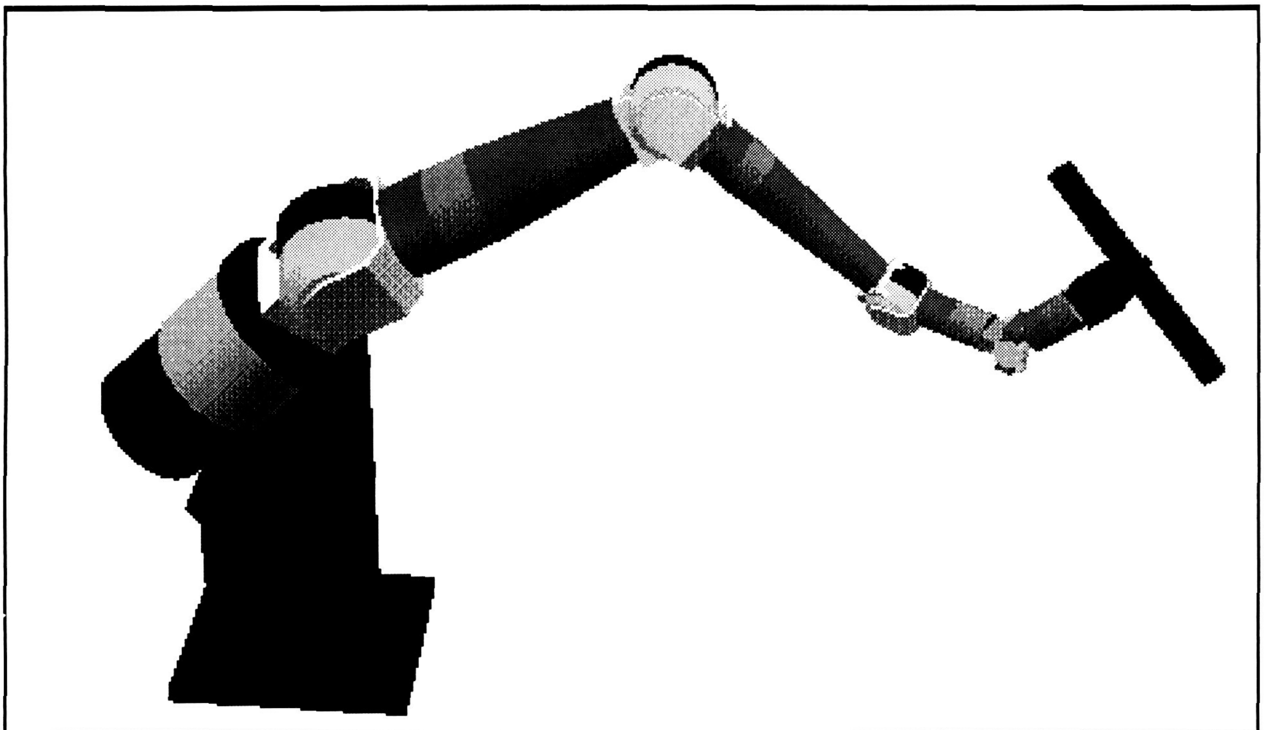

Figure 4. A conceptual fault-tolerant robot with 10 degrees of freedom.

In the decision-making and control algorithm for this system, the fault-detection and identification sub-system identifies the faulty joint and informs the decision making sub-system. The decision making sub-system selects any six joints of the robot for application of the inverse kinematics subsystem. The inverse kinematics sub-system then returns the joint displacements to the decision-making sub-system or an error flag if the calculations were unsuccessful due to mathematical singularity or workspace violations. The entire decision-making and control system executes at approximately 300 Hz. on an Indigo R4400.

DUAL ARM OPERATIONS

An advanced 17 degree-of-freedom dual arm robotic system, shown in Figure 5., is being integrated into a technology demonstration testbed in the UT Robotics Laboratory. The robot is capable of demonstrating Level III fault tolerance with each of its redundant DOF arms and Level IV fault tolerance with its dual arm configuration.

The robot utilized in the UT testbed is a K/B-2017 Dexterous Manipulator manufactured by Robotic Research Corporation [Karlen et al.] It incorporates two seven-axis manipulators on a three-axis torso assembly providing a total of 17 DOF. Grippers attached to the end of the manipulators each provide an additional DOF, making the entire system 19 DOF. Each joint drive module is comprised of an electric servomotor, harmonic drive gear reducer, and joint position and torque transducers.

Control of the system will be based on a task oriented architecture. A robot task such as application of a large force or precise motion of the end-effectors would be identified by the operator for a given operation. The operator may then concentrate on task completion while the robot's command and control architecture manages the robot's redundant resources and makes compensations for any system faults. The control system determines the best robot motion or arm poise to meet the physical task requirements by optimizing one or more of a set of dual arm performance criteria.

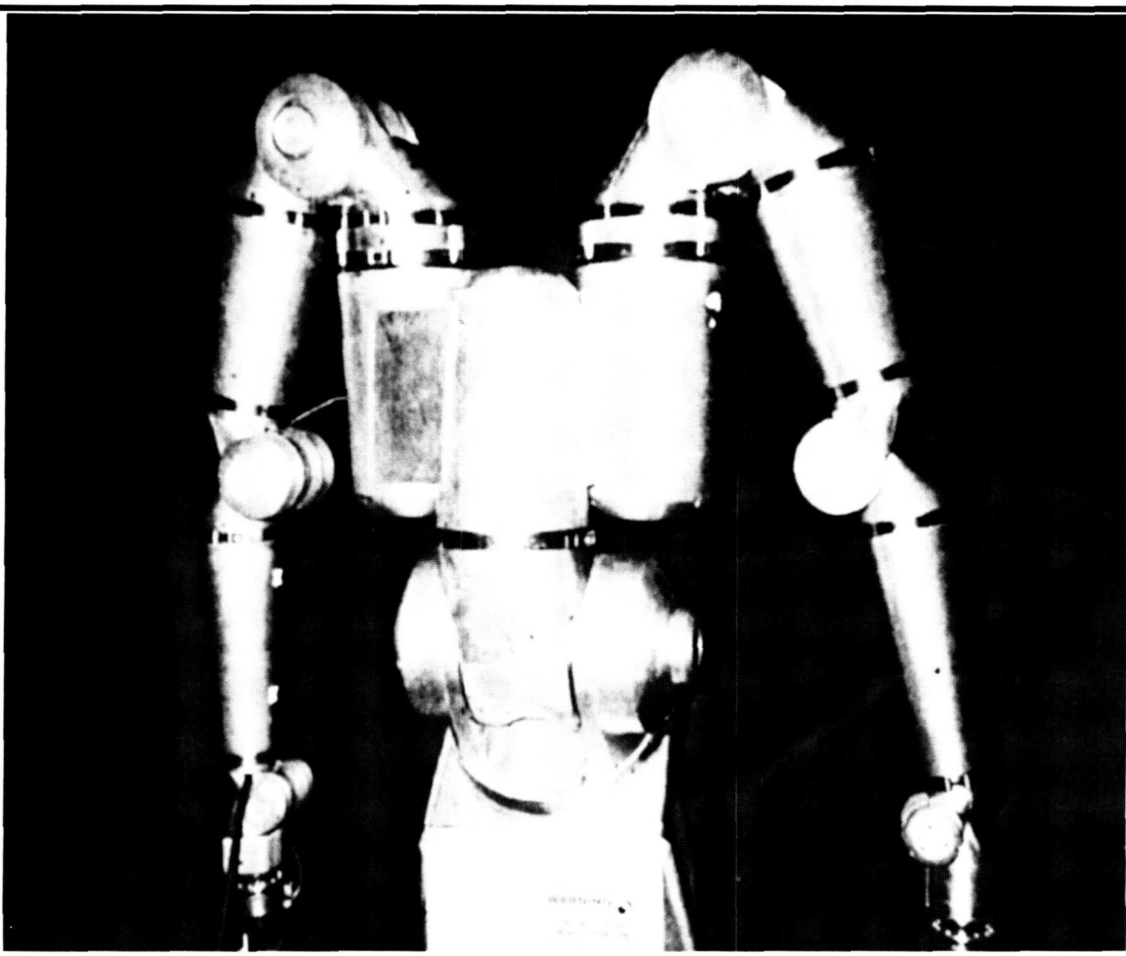

Figure 5. The Robotics Research Co. KB-2017 dual-arm robot.

The UT program has identified and mathematically formulated 25 dual arm criteria. The criteria are addressed at three separate levels of control: Operation level, End-Effector level, and Manipulator level. At each level, criteria are used to characterize different distinct kinematic and dynamic attributes. Multiple criteria have been successfully demonstrated in computer simulated dual arm task [Cox]. The task include heavy payload lifting, fixtureless assembly on-the-fly, and work piece deformation.

Failure Detection and Isolation

The subject of machine self-diagnostics and failure detection and identification (FDI) in dynamic systems is not new [Willsky][Isermann], but the integration of such schemes into a real-time failure responsive control system is yet to be realized. A key element of such an FDI scheme is its capability to detect *incipient* failure, which gives the reconfiguration and recovery stages ample time to respond to the failure in such a manner as to minimize error excursions and reconfiguration shock.

Two basic types of FDI schemes exist: model-free and model-based methods. The latter methods are more suited for real-time autonomous systems as the former invariably tend to be off-line and require operator assistance. Model-based methods rely on the use of mathematical descriptions of the monitored system, called *analytical redundancies*. The methods involve the generation of a *residual*, whose on-line statistics are compared against nominal ones in a decision unit where fault detection, isolation and identification take place. The decision unit then generates a control impairment status (CIS) report, that provides quantitative and qualitative information about the status of the monitored system, based on which the failure responsive control system takes subsequent actions.

The University of Texas has been investigating FDI techniques for robotic manipulators. A sensor fault detection scheme that employs parity relations among temporal redundancies has been derived [Sreevijayan] and implemented [Rubin] for the knuckle module of Figure 1. The failure of any one sensor (position or velocity) is masked, thus making FDI and sensor reconfiguration transparent to the control system . The scheme, as designed, can be configured in a triple or n-modular redundancy (NMR) setup so that faulty sensors can be isolated and dynamically configured out of the system. Actuator FDI for the knuckle is realized using parameter identification techniques based on the work in [Isermann]. In this technique, failure is detected and identified depending on the statistical variations of the on-line estimated values of the physical parameters of the actuator from their fault-free ones. The changes, in orientation and magnitude, of on-line estimated vectors in parameter space provide the necessary diagnostic information.

Reconfigurable Control

The problem of control of fault-tolerant systems, in particular those with redundant control inputs is of sufficient general interest across a variety of disciplines (robotics, flight control systems, etc.) that it warrants the investigation and development of a general theoretical framework. While preliminary efforts at deriving fault tolerance schemes that take into account the full dynamics of a manipulator have met with success [Menon][Ting], the absence of a formal mathematical framework restricts our ability to answer qualitative questions like existence and optimality of solutions to such problems. With this in mind, the University of Texas program has embarked on an in-depth study of the theoretical issues underlying the utilization (under normal and failure modes) of redundant control elements in general nonlinear control systems. We are currently pursuing an operator-theoretic approach which treats the control problem in an input-output framework. The problem is then to solve appropriate operator equations that yield infinite solutions by optimizing a prescribed functional. The functional so prescribed will reflect useful criteria during normal operation and will reflect the failure status of control actuators when the FDI system signals a fault. The mathematical framework may be thought of as generalizing the familiar generalized inverse problem in robot kinematics to the more complex realm of operators that map, say, one Hilbert space into another. We expect to be able to fully and formally characterize the nature of redundancies in any control system, in a manner analogous to the concept and formulation of *available redundancy* in the kinematics of Level III manipulators [Sreevijayan].

CONCLUSIONS

The University of Texas at Austin's Robotics program has developed a broad technical base for the development of component and system level technologies for space robotics. This paper gave an overview of our ongoing work in several key areas that are geared to address the needs of NASA's future missions. Our emphasis, driven by the needs of such missions, continues to be on enhanced accuracy and performance, condition monitoring and condition-based repair, modularity, criteria-based decision making and, above all, fault tolerance with reconfigurable control. To support the stated goals of our mission, and to fully integrate the component technologies described in this paper, we are also doing an in-depth study of micro-sensor technologies, sensor fusion and software architectures for failure-responsive control. This will allow us to realize the kind of machine intelligence that will animate the robots of the future.

REFERENCES

Chladek, J.T., "Fault Tolerance for Space Based Manipulator Mechanisms and Control System," *First International Symposium on Measurement and Control in Robotics,* Houston, Texas, June 1990.

Cleary, K., Tesar, D., "Decision Making Criteria for Redundant Manipulators", Presented at the *NATO Advanced Research Workshop*, Salo, Italy, June 1988.

Cox, D., Tesar, D., "Multi-level Criteria for Dual-Arm Robotic Operations", *Proc. of the 1994 IEEE International Conf. on Robotics and Automation*, San Diego, CA, pp. 1243-1249, May 1994.

Eschenbach, P.W., Tesar, D., "Optimization of Four-Bar Linkages Satisfying Four Generalized Coplanar Positions", *Journal of Engineering for Industry*, pp. 75-82, February, 1969.

Isermann, R., "Model Based Fault Diagnosis and Supervision of Machines and Drives", *Proc. of the 11th IFAC World Congress*, Vol. 4, pp. 1-12, Tallinn, Estonia, August 1990.

Karlen, J.P., et al., "Design and Control of Modular, Kinematically-Redundant Manipulators", Second AIAA/NASA/USAF Symposium on Automation, Robotics, and Advanced Computing for the National Space Program, March 9-11, Arlington, VA, 1987.

Menon, V.K., Sreevijayan, D., and Tesar, D., "A Preliminary Torque Redistribution Scheme for the Operation of Fault Tolerant Serial Manipulators", *Proc. of the International Symposium on Measurement and Control in Robotics*, Turin, Italy, Sept. 1993.

M.D. Rubin, " Development of Real-Time Operational Software for a Fault-Tolerant Testbed", Masters Thesis, University of Texas at Austin, Austin, Texas, June 1993.

Sreevijayan, D., "On The Design of Fault-Tolerant Robotic Manipulator Systems," Masters Thesis, University of Texas at Austin, Austin, Texas, May 1992.

Tesar, D., "Thirty-Year Forecast: The Concept of a Fifth Generation of Robotics--The Super Robot", *ASME Transactions on Manufacturing Review*, Vol. 2, No. [illegible], pp. 16-25, March 1989.

Butler, M. S. and Tesar, D., "A Generalized Modular Architecture for Robot Structures," *Manufacturing Review,* Vol. 2, pp. 91--118, June 1989.

Tesar, D., Price, C., Sreevijayan, D., "Four-Level Fault Tolerance in Manipulator Design for Space Operations", Presented at the *First International Symposium on Measurement and Control in Robotics,* NASA Johnson Space Center, June 20-22, 1990.

Ting, Y., Tosunoglu, S., and Tesar D., "A Control Structure for Fault-Tolerant Operation of Robotic Manipulators," *Proceedings of the 1993 IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 684--690, Atlanta, Georgia, May 2--7, 1993.

Van Doren, M.J., Tesar, D., "Criteria Development to Support Decision Making Software for Modular, Reconfigurable Robotic Manipulators, The University of Texas at Austin, Report to U.S. Dept. of Energy under Grant No. DE-FG02-86NE37966, March 1992.

Willsky, A.S., "A Survey of Design Methods for Failure Detection in Dynamic Systems", *Automatica,* Vol. 12, pp. 601-611, 1976.