DECISION MAKING SOFTWARE FOR DUAL-ARM OPERATIONS IN NUCLEAR FACILITY DECONTAMINATION AND DISMANTLEMENT

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ABSTRACT

Nuclear facility dismantlement tasks include disassembly of process equipment, cutting pipe, size reduction of equipment, transport of materials, and decontamination of floors, walls, and remaining equipment. A human performing these tasks would clearly consider a range of options and evaluate theses options based on a number of performance criteria. For remote systems to approach this level of sophistication, they must also consider and evaluate options based on performance criteria. For dual-arm robots, these criteria include: joint motion limits (ranges, velocities, accelerations, torques, etc.), dual-arm criteria (relative criteria for load, energy, compliance, etc.), obstacle avoidance (scene model for obstacles), and task criteria (force, deformation, dexterity, etc.). This paper discusses performance criteria and decision making algorithms implemented in software as teleoperator control modes. It includes implementation results for a dual-arm robot with 17 independently driven joints.

KEYWORDS: robots, decision making, dual-arm, dismantlement, teleoperate

INTRODUCTION

The United States Department of Energy (DOE) established the Office of Technology Development with the mission of cultivating technologies that are safer, faster, more effective, and less expensive than current methods. As part of the Robotics Technology Development Program, the Decontamination and Dismantlement (D&D) team designed and recently demonstrated the Dual Arm Work Module (DAWM). The DAWM (Figure 1.) is a robotic manipulator system with 17 Degrees of Freedom (DOF) arranged in 2 serial chains each having 8 independent DOF and sharing 1 common center rotational joint. This arrangement gives the system 5 redundant DOF.

Red Zone Robotics manufactured and delivered the 5 DOF base unit that includes the common rotational joint and the next two joints in both chains. A pair of Schilling Titan II manipulators form the last 6 DOF in each chain. The DAWM's kinematically redundant design allows it to perform a wide range of tasks, thus amortizing development costs. Currently, a human operator directly deploys the DAWM's 5 base joints using visual feedback, experience, and intuition. Because of obstacles or kinematic coupling among the robot's joints, even an experienced operator may need to reposition the base joints several times while performing a task. This paper describes several levels of computer involvement that should offer improvement.

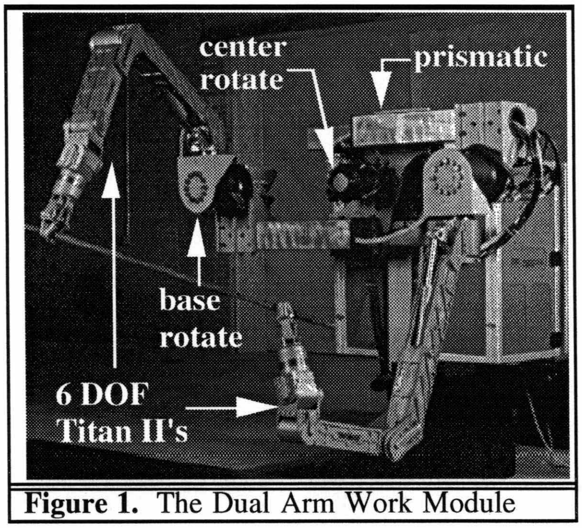

Figure 1. The Dual Arm Work Module

In the initial operational mode envisioned for the DAWM, the operator directly positions each of the 5 base joints using rate control and then leaves these joints locked while controlling the Schilling arms with a pair of force reflecting manual controllers. This is the classic model of DOE teleoperation; an experienced operator directly controlling a state-of-the-art robot. The present work develops a configuration control interface that drives a computer optimization algorithm with task requirements and performance criteria to automatically suggest a configuration for the robot's 5 base joints.

Results included in this paper show that the configuration control interface will successfully find collision-free configurations for the DAWM even in complex environments with nested obstacles. By associating a suite of performance criteria with each of the D&D tools the robot will use, the optimization algorithm will automatically prioritize and scale the performance criteria without requiring operator input. The operator retains the opportunity to adjust the ranking and scaling of these parameters if so desired.

The development of the configuration control interface also led to the development of two other useful operational modes. By automatically performing the required geometric transformations, **self-motion mode** allows the operator to hold the tool point constant while repositioning the base joints. **Coupled mode** automatically operates the DAWM's entire joint set in concert while the operator controls the tool point placement.

PERFORMANCE CRITERIA

Multiple performance criteria form the basis for decision making in this work. These criteria emphasize task-based performance indicators derived from the physical description of the manipulator. The origins of these criteria are from foundation activity in high speed mechanisms for production machinery (Benedict and Tesar, 1978). There, the issues of precision and modeling of complex non-linear structures forced the development of a geometric understanding for mechanical structures and how to represent them with efficient analytical tools. Thomas and Tesar (1982) showed that the concept of kinematic influence coefficients (used in systems with 1 DOF) were effective in spatial manipulator structures with N DOF. An important development in this continuing work on performance criteria has been the association of performance criteria with the D&D tools the DAWM will use while performing its tasks. By choosing a tool, the operator will automatically scale and prioritize the criteria. This automatic process allows the use of multiple performance criteria without distracting the operator from the task at hand or consuming valuable time.

The criteria formulations emphasize efficiency and portability. With currently available computational hardware, decisions based on several of these criteria are possible in real-time. Given the rapid pace of advancements in computational speed, it will soon be possible to employ the entire suite of performance criteria in a real-time decision making process. Table I. lists the general categories of these performance criteria.

TABLE I. General categories of performance criteria.

Category	Characteristics
constraint criteria	physical limitations
geometric	task independent
inertial	from dynamic models
compliance	design and operational issues
kinetic energy	content and distribution

The constraint criteria involve rapidly-calculated elementary formulations. The robot's physical limitations form the basis for these criteria. These limitations restrict joint travels, joint speeds, joint accelerations, and joint torques. The Joint Range Availability (JRA) is representative and formulated as: $\mathrm{JRA} = \sum_{i=1}^{n}\left[\frac{\left(\theta_i - \tilde{\theta}_i\right)^2}{\theta_{i\,\max}^2}\right]$, where θ_i is the joint displacement, $\tilde{\theta}_i$ is the mid-range displacement and $\theta_{i\,\max}$ is the displacement at the joint limit. JRA measures the joint's displacements away from their midpoints.

The Jacobian matrix forms the basis for the geometric performance criteria. These criteria are task independent and based only on the geometry of the robot; thus these criteria are formulated once for each robot with no need for reformulation if the task changes (Cleary and Tesar, 1990).

The inertial criteria have their basis in dynamic models of forces and torques within the robot and are essential to the intelligent design and application of robots. These criteria mainly address actuator torques and their rate of change. The rate of change of the actuator torque criterion, $\eta_{\Delta\tau}$, follows as: $\eta_{\Delta\tau} = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial \lambda_{\max}}{\partial \theta_i}\right)^2}$, where $\lambda_{\max}$ is the maximum eigenvalue of the effective inertia matrix. This criterion measures how fast the robot can respond to torque and force demands. It is an especially important criterion because larger actuators or higher gear ratios can supply more torque, but both will slow the overall response of the robot to external disturbances. Consideration of the basic torque demands as well as their rate of change allows the intelligent allocation of the robot's torque resources for enhanced operation.

The compliance criteria describe the robot's ability to perform precision operations under load. They also correspond to the vibratory modes of the robot. The potential energy partition values are particularly important compliance criteria. These values measure the distribution of compliance energy and how it changes as the robot moves. An unusually high compliance energy content in any part of the robot indicates a problem with the robot's design. Rapid changes in the compliance energy distribution indicate large local forces, which correspond to large actuator demands and decreased precision.

The kinetic energy criteria address high-level issues represented in relatively simply formulations. The rate of change of the kinetic energy, $\eta_{\Delta\kappa}$, is an important criterion and formulated as follows: $\eta_{\Delta\kappa} = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial \eta_{\kappa}}{\partial \theta_i}\right)^2}$, where η_{κ} is the 2-norm of the eigenvalues of the effective inertia matrix. Large changes in kinetic energy correspond to very large demands on actuator power. Very rapid changes in the kinetic energy distribution represent shocks to the robot.

DECISION MAKING

While most roboticists will intuitively agree that multiple criteria assess the true performance of a robot, incorporating these criteria in real-time decision making is a challenging pursuit. This report describes a method that combines closed-form reverse position analysis, null-space exploration, and a multicriteria evaluation process. The closed-form reverse position analysis satisfies the placement constraints on the robot's End-Effector (EEF). The process of null-space exploration generates configuration options. The evaluation process uses the performance criteria to rank the options and choose one as the recommended configuration.

Many researchers have studied this decision making problem in the context of resolved motion control for redundant robots. The coupled operational mode described in this section is an example of resolved motion control. Most resolved motion control work derives from Whitney's (1969) resolved motion rate control that suggests the use of the pseudo-inverse for redundant robots. Liegeois (1977) showed the extension of this method to include self-motions via the null-space. Since then, a large number of researchers have implemented pseudo-inverse based methods and others have studied their limitations (Maciejewski, 1989). Other rate control approaches include: Seraji's (1992) configuration control, Baillieul's (1986) extended Jabobian, the Jacobian transpose (Das, Slotine, and Sheridan, 1988), and a number of numerical optimization methods such as the series of unconstrained minimizations technique. Dubey and Luh (1988) include task-based performance measures in the redundancy resolution.

This decision making work applies an entirely different redundancy resolution method (Hooper and Tesar, 1995). By incorporating closed-form reverse position analysis, this method leverages two decades of work since Freudenstein's (1972) declaration of general six DOF reverse position analysis as the Mount Everest of kinematics problems. Other researchers (Crane, Duffy, and Carnahan, 1991) have also shown the use of closed-form reverse position analysis to solve 6 DOF substructures within a redundant robot, though they leave the decision making to a human operator.

The decision making algorithms fall into two general categories depending on the operational mode. In the configuration control mode, the interface suggests one configuration based on task requirements and information on the environment. The software generates the suggestion using a simulated annealing algorithm. In the coupled mode, the software continuously updates the set of joint displacements as the operator "steers" the robot's hands with a manual controller. For this mode, the software employs a sequential filters optimization algorithm.

Implementing the configuration advisor presents a challenging decision making problem. Given the desired tool-point locations, the varied set of performance criteria, and a complex environment with multiple obstacles, the advisor must identify a single solution within the DAWM's 17 degree of freedom solution space. This is a geometrically complex global optimization problem in an extremely large solution space. Figure 2. shows a collision-free suggestion in an obstacle-strewn environment generated by the configuration advisor.

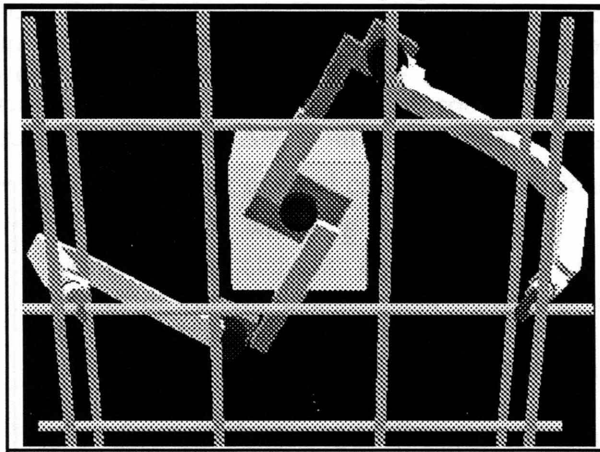

Figure 2. Collision-Free configuration suggested by the configuration advisor.

Table II. lists some options for finding global optima. These options include: a "shotgun" approach tracking gradients from different starting places in the workspace, simulated annealing based on a model of the physical annealing process, genetic algorithms based on a model of biological genetics, brute force exhaustive evaluation, and the Monte Carlo based on randomness and statistics. All of these methods will solve global optimization problems. The difficulty lies in the need for interactive response (a few seconds) from the configuration advisor. This section discusses results for the simulated annealing method. The results show this to be a reliable approach, even in complex environments with multiple obstacles and competing performance criteria.

TABLE II. Characteristics of global optimization methods applicable to D&D operations.

Method	**Basis**	**Guaranteed Global**
shotgun	gradient tracking	no
simulated annealing	probability distribution	no
genetic algorithms	genetics in biological systems	no
brute force	explicit evaluation of function	yes
Monte Carlo	randomness and statistics	no

Annealing describes a process of heating a material to an elevated temperature and then cooling it very slowly. The slow cooling allows the material to reach a low energy state in which it is relatively ductile. With no intelligence or systematic strategy, some materials minimize their energy state during slow cooling. Simulated annealing is an approximation of this natural process carried out on a computer and is based on the Boltzmann probability distribution.: $\mathrm{Prob}(E) \approx \exp\left(-\frac{E}{kT}\right)$. In this equation, E is the energy of the system, k is Boltzmann's constant, and T is the temperature. Essentially, the Boltzmann probability distribution states that a system's energy is probabilistically distributed depending upon the temperature. As the temperature increases, the probability of the system assuming a higher energy state increases. As the temperature is lowered, the odds of the system leaving a lower energy state decrease. Because simulated annealing algorithms sometimes leave lower energy states for higher ones, they can escape from local minima. Simulated annealing algorithms typically include a method of generating random changes in the system's configuration. As applied to the configuration control problem, these changes represent trial configurations – options for the robot. The algorithm evaluates these options using the Boltzmann probability complex dual-arm robot with 17 DOF designed specifically for D&D operations. For this robot, results show the method is powerful enough to operate the robot in a complex environment with multiple nested obstacles, yet efficient enough to execute at hundreds of cycles per second on common personal computing hardware.

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Proceedings of the World Automation Congress (WAC '96) **May, 1996**

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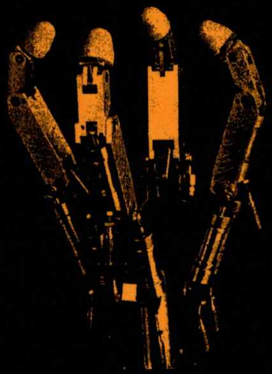

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TSI Press Series *Albuquerque, NM, USA*