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DUAL ARM WORK PACKAGE PERFORMANCE ESTIMATES AND TELEROBOT TASK NETWORK SIMULATION*

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ABSTRACT

This paper describes the methodology and results of a network simulation study of the Dual Arm Work Package (DAWP), to be employed for dismantling the Argonne National Laboratory CP-5 reactor. The development of the simulation model was based upon the results of a task analysis for the same system. This study was performed by the Oak Ridge National Laboratory (ORNL), in the Robotics and Process Systems Division. Funding was provided the U. S. Department of Energy's Office of Technology Development, Robotics Technology Development Program (RTDP).

The RTDP is developing methods of computer simulation to estimate telerobotic system performance. Data were collected to provide point estimates to be used in a task network simulation model. Three skilled operators performed six repetitions of a pipe cutting task representative of typical teleoperation cutting operations.

INTRODUCTION

The Cross Cutting and Advanced Technology (CC&AT) effort within the U.S. Department of Energy's Robotics Technology Development Program (RTDP) is charged with developing technology that is required for a wide variety of robotics projects. Part of the CC&AT is engaged in developing simulations for use in support of RTDP robotics projects. This paper describes work conducted at the Oak Ridge National Laboratory in the Robotics & Process Systems Division to develop task network simulations. Specifically, it addresses work done in support of the CP-5 reactor decontamination and decommissioning project.

The CP-5 Reactor is a heterogeneous, heavy water cooled and moderated, fully enriched reactor designed to provide neutrons for research purposes. It is pierced by several horizontal and vertical tubes designed for access to the neutron flux of the reactor. The reactor was shut down in September of 1979 when it was determined no longer useful for then current research needs. In 1989 the SAFSTOR program was implemented to ensure the safe storage of part of the reactor's components. Today with much of the reactor still remaining, the CP-5 Reactor Decontamination and Decommissioning Project is assigned the responsibility of robotic-assisted removal of the octagon-shaped biological shield with experimental penetrations, aluminum reactor tank, graphite reflector and steel tank.

As part of an ongoing effort to provide cost-efficient methods of robotic systems evaluation and development to the RTDP, MicroSAINT task network modeling continues to prove an invaluable tool in developing models of missions involving the use of robotic systems where direct human intervention is made dangerous due to environmental hazards such as radiation exposure. The CP-5 Reactor model is an attempt to analyze the task events leading to mission completion with criterion including speed of operation. Independent variables that will be manipulated in the evaluation include task sequence pathways, the presence or absence of some reactor parts, and tooling methods.

The purpose of the CP-5 MicroSAINT Network Model is to provide an efficient means to determine which of several alternative methods of performing CP-5 decommissioning tasks is most beneficial, considering cost, safety, speed and quality factors. The model seeks to develop relevant tool, task, and manipulator prioritization, and estimate task time and feasibility.

Simulation can be used to support a quantitative performance evaluation of proposed robotic systems, even before these systems are built or installed. The two most frequently mentioned control systems are teleoperation and supervisory control. Teleoperation requires continuous manual positioning of the manipulator and end-effector for waste retrieval operations. Supervisory control requires the user to program and verify control maneuvers off-line before allowing the automatic control system to execute the maneuvers. In both cases a human user monitors system performance with the assistance of video monitors, although in supervisory control the human user may instead monitor a graphic world model of the tank interior and manipulator.

TASK NETWORK SIMULATION

Task network simulation is based on the human factors technique of task analysis, used to decompose a mission into the most discrete elements possible to describe the task components necessary to mission completion. In MicroSAINT, tasks are represented as networks composed of task elements. Pathways represented by arrows connect the networks and the task elements inside the network. As the simulation progresses from task to task data are collected on the average times to completion and other defined variables in the model. After any given activity a decision node consisting of if-then types of conditions may be encountered at which time the computer software makes a decision on the pathway that will be used to continue the simulation.

A network diagram shows the constituent parts of the simulation model. It is essentially a task block flow diagram where nodes represent activities of the system. In order to create a network, a task analysis is performed to identify the activities of the system. The network also shows the path or paths followed after completion of each activity. The network diagram can be implemented as a computer-based network simulation model using a network simulation package such as MicroSAINT.

Task networks, represented as rectangles in flowchart format, are the highest level of an abstract hierarchy that may consist of as many levels as needed to represent the task in its most primary form or descriptive level. Each task element, represented as an oval, requires entry of several parameters defining the conditions under which the activity takes place. Average time, standard deviation and distribution type must be entered in order for data to be generated. Four conditions may be defined to place restrictions on the task event or to define additional variables to generate data. A release condition defines under what conditions the task may take place. Launch and beginning effects define what happens after the beginning of task execution. An ending effect defines what occurs at the end of task execution.

Multiple pathways, multiple entities, and queues can be defined, making the MicroSAINT package a very useful tool to describe activities which occur simultaneously and activities such as disassembly in which parts accumulate, creating a stockpile to be processed. When the model is fully prepared a simulation run will generate data based on the chosen distribution type and the task parameters giving the researcher the opportunity to analyze a quantitative dataset with the inherent advantages of generalization of results. The results are only as good as the task parameters, however, so caution should be taken when interpreting results generated from methods other than time and motion studies.

The CP-5 simulation model was developed with the MicroSAINT package, a network simulation modeling tool kit for personal computers. Network simulation is a suitable tool for modeling systems that can be decomposed into a set of discrete chronological steps or tasks. A set of tasks and pathways (which connect tasks according to their precedence relationships) constitute the network. There are important advantages of decomposing a complex system into smaller steps: it is often easier to describe the behavior of constituent parts of a process than to describe the whole, and the performance of the whole system can be studied by varying the behavior of the constituent parts. The set of steps may be organized as an abstraction hierarchy, where the top level reveals the most general view of the operation of the network. Each box in the top level contains a sub-network, which in turn may contain its own sub-network, etc. Successive levels in the hierarchy show more detail of smaller parts of the entire system.

Simple networks process tasks one at a time in sequential fashion. More complex networks allow multiple entities to propagate through the network in parallel fashion. Thus it is possible for multiple tasks to be processed concurrently in such networks. Tactical and multiple branching also create the possibility that entities will follow novel paths through the network on different simulation runs. Examples of network modeling for complex manned systems[1,2] and a simple example of a MicroSAINT model application in human-robot interaction[3] may be found elsewhere.

The task network model was produced based on the functioning capabilities of the DAWP. Primarily, five basic manipulative tasks provide the core of the model's parameterization of the mission. These generic tasks include (1) Positioning (2) Reaching (3) Grasping (4) Cutting and (5) Releasing. Positioning includes moving the manipulator arm to a beginning point in alignment with the area of the reactor to be worked upon. Reaching is defined as moving the manipulator toward an object or area that will be manipulated. Grasping occurs when the manipulator tongs are closed with an object or tool in between them. Cutting occurs when a cutting tool is in the manipulator's grasp and the arm is positioned in relation to the object to be cut. Releasing occurs after an object has been grasped by the tongs and is moved to a disposal area for reduction or packaging.

Model Development

The CP-5 Reactor simulation model is being developed in order to provide a performance benchmark for the disassembly of the reactor. Prior to its' implementation, criteria of importance to performance were specified for modeling purposes. Speed of operation was deemed to be vital to the modeling of system performance as a whole.

Task Network. The disassembly of the CP-5 Reactor is based on the assumption that the reactor may best be taken apart in the reverse order from which it was assembled. The task analysis was extrapolated from an existing dismantling plan[4] and a tooling evaluation.[5] The evaluation delineated the tasks and tools necessary to perform the disassembly of the reactor. Manual portions and robotic portions were specified. Also, for some tasks different options for performing the activities were provided.

Midway into the development of the CP-5 Reactor MicroSAINT model it was determined that dismantling would proceed in a side-to-side fashion, that is, the DAWP will rest on one side of the reactor and work on the other until objects within reach have been removed, and then be repositioned to work on the first side. In order for the dismantling to proceed in this manner, a task network simulation was created to model the process of having to install and reinstall the manipulator system when it had to be strategically moved to reach a portion of the reactor. The DAWP network is important in that it will occur several times throughout the model taking up a fair amount of performance time and thereby affecting the evaluation of overall system performance.

Model Variables. Five major variables keep track of time spent (1) positioning the manipulator (2) reaching (3) grasping (4) cutting and (5) releasing objects. Mean and standard deviation variables were created for each of the five major variables. Additionally, variables were created for the purpose of analyzing the percentage of total time spent positioning, reaching, grasping, cutting and releasing. Counter variables were created to count the number of parts removed, for example, the number of bolts removed in a single network. Other counter variables were created for cases in which the number of parts was given. These counters count down to zero when the entity is then allowed to move on to the next task element. In order to allow decisions to be made at specific points in the model, additional variables were created that when initialized to 1 or 0 enable the entity to follow one of two possible pathways. A variable to keep track of the amount of time the entity spends waiting in the queue was also created.

Performance Estimation

A task network simulation is as good as the performance parameters it is based upon. Four sources of performance estimates are available to simulation developers. These are, in order of ascending reliability and validity:

1) **Estimates**: subject matter experts, those familiar with a task, may be asked to estimate the time that it will take to perform a task, the variability that may occur in task performance, and the types and frequency of errors that may occur. This method is relatively inexpensive but produces estimates that are less trustworthy than other methods. However, this is often the only source of performance estimates that is available to a developer, particularly in early phases of model development.

2) **Task decomposition:** One of the advantages of task network simulation is that the modeling tool is vertically extensible, that is, it may be expanded in detail. When tasks can be broken down to very small components, it is possible

to calculate or assign performance values based on (1) human motor performance laws or (2) predetermined time-motion study data.

3) **Mock-up performances:** Tasks may be mocked-up either in the real world or in a virtual world and human operators can complete the tasks. Direct observation of key performance parameters may be made in either case.

4) **Task analysis:** Where tasks are already being performed, traditional task analysis methods may be used to directly observe performance. This is only useful in the case of pre-existing sub-tasks, and is not usually available to telerobot simulation developers.

TELEOPERATOR CUTTING TASK EXPERIMENT

Recently a data collection campaign was conducted at RPSD to provide data for the CP-5 task network model. Specifically, it was intended to provide mock-up-based performance estimates for two key DAWP tasks: reaching and cutting.

Methods

Teleoperator. The teleoperator was the Dual Arm Work Module (DAWM) installed in the Robotic Technology Assessment Facility at ORNL. The DAWM is a dual-arm, hydraulic manipulator controlled by non-replica master controllers. Control is position-position using Cartesian transformations from master space to slave space. The DAWM provides force reflection to users based on data provided by force/torque sensors located at the wrist of each manipulator arm. The DAWM is a partial version of the CP-5 DAWP, lacking only the integrated television viewing systems that are a part of the DAWP, and featuring full-scale master controllers rather than the mini-masters used for DAWP.

Operators observed the remote site by closed circuit television cameras mounted on the DAWM. There were two cameras just above the arms, one on each side of the DAWM. There was a third camera mounted between the arms. Operators were free to use any camera view available during the task but were not allowed to move the cameras during the task.

Task. The operators used the DAWM and a hydraulic cutter to cut six sections of 2.5 cm stainless steel tubing mounted on a mock-up rack. The tube sections were approximately 1 meter long, and operators cut a section approximately 75 cm long from each pipe.

Participants. Three highly trained and experienced teleoperator users participated in the experiment. All were males between the ages of 35 and 45, right-handed, with normal vision. Each operator completed 6 repetitions of the task but only the last 5 were used in the analysis (the first repetition for each participant was discarded as a practice trial).

Procedures. Operators were briefed about the data collection program before it started but they were not informed of the purposes of the experiment until after data collection was completed. In each testing session, an operator completed a single repetition of the task. Operators were not permitted to know their times for completing the task, nor were they permitted to know the time required by other operators to do the task.

Each task repetition required about 4 minutes. To prevent them from becoming too fatigued to perform well and from responding automatically to questionnaire items, operators did not perform consecutive task repetitions.

Variables

Task Performance. Task performance was measured as the time, in seconds, required to complete the pipe cutting task. The times required to complete sub-tasks were also recorded. Sub-tasks included "Position manipulator," "Cut 1," and "Cut 2." The Position manipulator sub-task included movement of the manipulator from the start point to the site of the first cut and movement from the site of the first cut to the site of the second cut. The Cut 1 sub-task included grasping the top of the tube section and operation of the hydraulic cutter. The Cut 2 sub-task included grasping the bottom of the tube section and operation of the hydraulic cutter. Ideally, the Position manipulator sub-task occurred 12 times per task repetition, the Cut 1 sub-task occurred 6 times, and the Cut 2 sub-task occurred 6 times. However, mistakes during the course of a sub-task could lead to the repetition of a sub-task.

Critical Incidents. Critical incidents from the ORNL teleoperator critical incidents checklist[6] were recorded to measure the quality of task performance and to allow estimation of the number of user errors that might occur during this type of task. Nine critical incidents were observed and recorded during task completion, including the following:

1) **Collision-manipulator**: the user unintentionally causes the manipulator to touch or strike an object in the remote site

2) **Collision-object**: the user unintentionally causes an object in the grasp of the manipulator to touch or strike an object in the remote site

3) **Damage object**: an object in the grasp of the manipulator or at the remote site is damaged during operations

4) **Incomplete release**: an object in the grasp of the manipulator, or in the grasp of a tool held by the manipulator, is not properly released, resulting in unexpected movement of the object when the manipulator moves away from it

5) **Mis-centering**: the end-effector or tool is mis-centered at the end of a goal-directed movement, requiring re-positioning of the manipulator to properly make contact with it

6) **Missing**: at the end of a goal-directed movement, the end-effector or tool misses the intended target (goal) of the movement

7) **Pressing**: the manipulator, end-effector, or a tool attached to either pushes against an object in the remote area hard enough to cause the object to move or bend

8) **Slip-reposition**: an object in the grasp of the manipulator slips and must be re-positioned in the end-effector

Results

Task Completion Time. Table 1 presents the averages and standard deviations observed during the pipe cutting experiment. On average, it required 217.8 seconds (3 minutes, 37.8 seconds) to complete the task with a standard deviation of 43.4 seconds. The two cutting tasks required more than twice as long to complete as the position manipulator task, probably because of the slow activation of the hydraulic cutter. It appears that the operators were able to complete the task in a reasonable period of time, and that neither the operators nor the manipulator itself were the most significant contributors to total task time; it was the hydraulic cutter which slowed down the operation the most.

Critical Incidents. Table 2 presents the number of each of the critical incidents observed during task completion, the percentage of total critical incidents, and the average number of incidents observed per trial. Critical incidents are anything that occurs which might provoke an evaluative response from an observer. They are not necessarily errors. Given the nature of the critical incidents, the number occurring during task completion was quite low, when one considers that each trial required twelve matings of cutter and tubing and twelve releases of the tubing by the cutter.. The total number of critical incidents was 58, averaging fewer than 4 per trial. Most of the incidents involved either missing the tubing with the cutter (22 or 38%). Collisions took place between the tool and manipulator and the tubing (10 total or 17%). Only 2 incidents involving damage, both involving bending or denting tubing or the tubing support structure. One of these occurred when a user cut a piece of tubing too high up the tube and sliced through a portion of the mock-up support structure.

Table 1. Task performance results.

Task/Sub-task	Average Time (seconds)	Time St. Dev.
Complete task	217.80	43.40
Position manipulator	5.22	9.66
Cut 1	15.18	9.20
Cut 2	13.71	11.34

Table 2. Summary of critical incidents.

Incident	Total	Percentage	Average per trial
Collision-manipulator	8	14%	0.53
Collision-object	2	3%	0.13
Damage object	2	3%	0.13
Incomplete release	6	10%	0.40
Mis-centering	7	12%	0.47
Missing	22	38%	1.47
Pressing	10	17%	0.67
Slip-reposition	1	2%	0.07
Total	58	100%	3.87

SUMMARY AND DISCUSSION

This paper described the motivation for developing task network simulations within the RTDP, recent developments in support of the CP-5 reactor project, and an experiment that provided time estimates for use in the task network simulation. These methods and data are applicable to other telerobot applications inside the RTDP. They are also useful to a broader class of robotic applications outside of RTDP.

Task network simulation can support robotic system development in all phases of the development cycle, as illustrated by Figure 1. During the first phase, in which system requirements must be established, network modeling supports the effort by allowing high-level mission models to be built, which provides a clear understanding of what the system must accomplish. During concept formulation, preliminary concepts may be modeled and their relative merits compared using performance data at hand. As system concepts mature, the network model can mature as well, and is capable of providing guidance on directing development efforts at the most rewarding (performance-wise) development areas. Sensitivity analysis may be conducted to evaluate the relative performance of the system with different components or using different approaches to sub-tasks. Finally, a mature model can be extended to the level of detail necessary to use in reliability and maintainability analysis.

Task network simulations provide insights not obtainable from graphic simulations because of the mission and user task orientation inherent in the approach. Therefore, it is an important part of overall RTDP simulation efforts.

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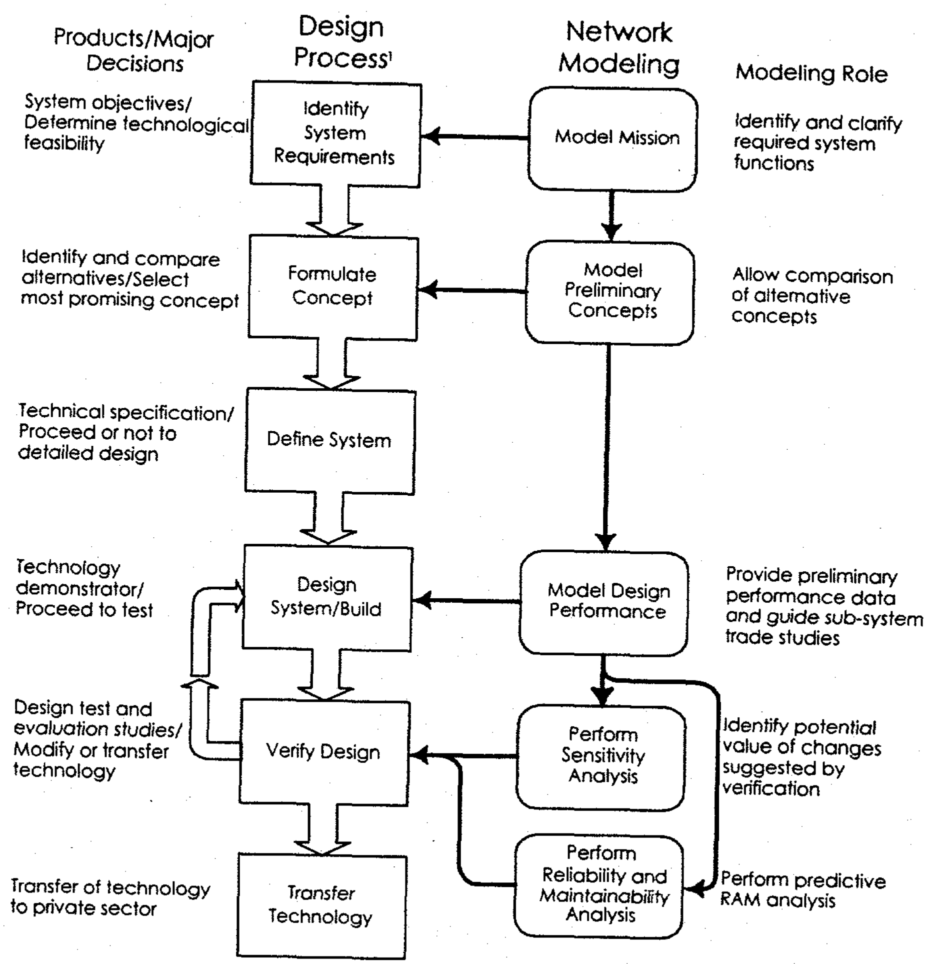

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Figure 1. Task network model inputs to the design process.

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