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ROBOTICS TECHNOLOGY DEVELOPMENT PROGRAM CROSS CUTTING AND ADVANCED TECHNOLOGY*

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ABSTRACT

Need-based cross cutting technology is being developed which is broadly applicable to the clean up of hazardous and radioactive waste within the U.S. Department of Energy's complex. Highly modular, reusable technologies which plug into integrated system architectures to meet specific robotic needs result from this research. In addition, advanced technologies which significantly extend current capabilities such as automated planning and sensor-based control in unstructured environments for remote system operation are also being developed and rapidly integrated into operating systems.

INTRODUCTION

As described in [1], the DOE Office of Technology Development's (OTD) Robotics Technology Development Program (RTDP) is structured into a number of major elements. Those elements comprise the subject areas of this workshop. Sandia National Laboratories serves as the Coordinator for the Cross Cutting and Advanced Technology element of the RTDP (referred to as CC&AT throughout this paper). As such, Sandia coordinates the activities of a multi-laboratory team (Oak Ridge National Laboratory, Los Alamos National Laboratory, and Pacific Northwest Laboratory in addition to Sandia). The CC&AT element of the RTDP stresses close teaming among the Laboratories to accelerate technology development while reducing overall costs. In addition to supporting technology development within the DOE Laboratory structure, CC&AT sponsors and integrates technology development within industry, university, and other governmental agencies sectors which can significantly impact RTDP and provide faster, safer, cheaper waste clean up. Strong emphasis is placed on the University R&D sector in order to leverage this extensive scientific and technology base.

The RTDP 5 Year Plan [1] states that robotic technologies used during waste cleanup should

- allow easy manual operation since the ill-defined environments characteristic of many waste sites will require close operator monitoring and control during remote operations,
- require a minimum of specialized operator training and use high factors of safety to improve system reliability,

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- have operator interfaces designed to minimize operator error and maximize overall system productivity,
- have enough intelligence to detect and prevent operator errors while maintaining active operator involvement,
- be as generic as possible and widely applicable to ER&WM activities within the DOE complex, and
- be flexible in operation to deal with situations not anticipated prior to the start of waste management and remediation projects.

THE CC&AT PROGRAM

In response to the characteristics of robotic systems outlined above, CC&AT has structured its robotic technology development activities into seven major thrust areas.

1. Sensing Systems
2. Controls
3. Systems Analysis
4. University R&D Programs
5. Cooperating Multi-Arm Manipulation
6. Modeling and Simulation
7. Technology Transfer

In addition, a DOE/Industry/University Forum is held annually to stimulate technology transfer and inform the community of RTDP activities.

1. Sensing Systems -- Sensing systems allow robots to adapt to unknowns in their environment. For example, sensors can locate objects and map environments so that the models used by the robot to automate operation are accurate. Sensors are typically quite generic and are useful in a very broad range of applications. Sensing systems within CC&AT fall into three broad categories:

- sensors for robot control,
- sensors for mapping the location of objects in the environment, and
- sensors for determining the radiological, physical, and chemical characteristics of waste.

CC&AT depends upon other technology development efforts to provide the majority of sensors needed for faster, safer, and cheaper operation of robot systems. As such, CC&AT interacts strongly with CTD activities such as the Characterization, Monitoring, and Sensor Technology Integrated Program. CC&AT only develops those sensors not under development by other organizations within OTD yet deemed important for the successful development of robotic systems. CC&AT sensing system activities adapt and integrate sensors for robotic deployment.

Robot control sensors provide inputs to the algorithms controlling robot motion. Sensors used during control must provide processed information at a high sampling rate. Sensors used in high-speed control include position (encoders and resolvers), force and torque, and proximity. Such control sensors allow rapid movement in ill-defined environments without collisions. Work within CC&AT in this area is currently focused on sensors for automatically avoiding robot collisions with objects in the environment.

Environmental mapping sensing systems are typically used to gain information about the location of objects in the environment and not for high-speed, real-time control of the robot system. Integration of such sensors into robot deployable systems allows the development of geometric models of the environment used by the robot system controller to automatically plan and execute robot actions. These sensing systems also assist the operator during manual operation to ensure safety. Examples of environmental sensing used for mapping include computer vision, ground-penetrating radar, and seismic sensing. Activities within CC&AT currently stress the development of highly modular, plug and play sensor system architectures (termed Mini-Lab) and the development of computer algorithms for automated fusion of multiple streams of sensor data and interpretation. Algorithms which incorporate the unique ability of robotic systems to accurately and repeatably position arrays of sensors need to be developed to allow extraction of high fidelity information about waste sites.

Physical and chemical characterization sensing systems provide the information needed to plan appropriate robotic remediation operations and to provide the information needed to formulate the most effective cleanup procedure with minimal environmental risk. Past work within CC&AT focused on robot deployable microsensors for chemicals. This work was completed in FY93 and no new further sensor development work in this area is underway. CC&AT will draw upon sensor technologies from other programs as needed.

2. Controls -- Faster, safer, and cheaper operation of robots used to clean up waste sites and handle hazardous materials is dependent upon the development of advanced control technologies. Current approaches to robot system programming is inadequate because operators cannot access the hazardous environments. Off-line programming of the robots will be needed using both computer models and operator assistance. Off-line programming also allows previewing of programmed robot motions by the operator before actual operation by the robot. This new approach to robot system control in hazardous environments has been successfully pioneered by CC&AT and requires the integration of advanced computing technologies, computer models of the robot and its environment, sophisticated actuator control algorithms, and sensors to map unknown environments and to allow servo control of the robot. Thus, robot system control encompasses computing and communication, software and algorithms, and man-machine interfacing. This approach to robot control is generic and applies to a broad range of robotic systems applied to ER&WM.

Computing environments that incorporate user-friendly, menu-driven operator interfaces with high-speed, real-time computing can safely control complex robot systems operating both in the relatively well-defined environments associated with automated laboratory and waste management facilities, and in unstructured environments similar to those anticipated during site cleanup. As advanced computing technologies become available, they will need to be integrated into the control architectures of robot systems. These environments allow increasing levels of modeling and autonomous sensor interpretation within the real-time computing constraints of robots. It is anticipated that OTD will not sponsor the direct development of computers, but will adapt new computing technologies to the needs of robot system control as they emerge.

Software and Algorithms development falls into three major categories: programming environments, modeling of geometric objects (including the robot and its environment, and sensor interpretation and modeling), and algorithms that represent the physical laws governing behavior of the robot and its interactions with its environment.

Advanced programming environments impact robotics technology in the broadest sense by improving the way in which the software that controls the robot system is constructed. Programming environments that stress structured software concepts and facilitate the development of highly modular software that can be reused in multiple projects are stressed within CC&AT to reduce the time and cost of technology development. Modeling allows the automation of robot operations and evaluation of operator supplied commands to the robot to ensure that only commands resulting in safe operation are executed. Such modeling, when coupled with graphics interfaces also provide natural, intuitive operator interfaces for robot programming. The geometric model underlying the graphic interface then automatically converts the graphic commands into the actual robot motion programs. The geometric models used for high level robot system control form the basis for full system simulations for design and analysis (see section below) Algorithms representing the physics underlying the interpretation of sensors and the control of the robot system impart intelligence to robot systems. Force control algorithms, for example, allow the in-contact motion required for many remediation operations. Sensor interpretation algorithms convert the electronic signals from sensors into knowledge of the robot's environment. All of these varied types of algorithms are developed within CC&AT to obtain higher performance from robot systems.

Man-machine interfacing employs human factor precepts to assure optimized interfacing. Perhaps the most important sensory feedback is remote viewing. In addition, technologies for providing non-visual sensory feedback such as force reflection to the operator require development. Such operator sensory feedback technologies must be carefully integrated into the overall robot system control so that the operator and sensor-based servo control systems do not counteract one another. CC&AT stresses the use of modular subsystems to allow ease of integration of man machine technologies into robot systems

3. Systems Analysis -- There are a large number of technology options for the clean up of waste sites. Although robotics technologies offer significant potential for reducing the cost and time for waste clean up while increasing safety, those advantages need to be quantified to ensure that the most promising technologies receive highest priority. Due to the hazardous nature of many waste sites, human entry will be proscribed. Past experience has shown that the use of conventional remotely operated equipment is slow (frequently 8 to 50 times longer than similar hands-on task execution times) and tedious. The economic costs and benefits of computer assisted robotic devices needs to be evaluated to help direct and prioritize technology development efforts within the RTDP. Increased safety and reduced operator training costs resulting from the automation of tedious remote tasks needs to be assessed.

The RTDP requires the development of general techniques for application to the evaluation of all robotics technology development efforts. CC&AT focuses on development of cost/benefit analysis techniques based upon sound life cycle cost assessment approaches. These cost/benefit analysis techniques are then applied generally within the RTDP to guide development activities.

4. University R&D Programs -- A key element in the faster, safer, cheaper clean up of waste sites involves the stimulation of advanced technology and accelerating the integration of innovations into waste clean up systems. The RTDP University R&D Program recognizes the strong technology base resident in the university community and provides a focused technology development program which stresses close interaction of the university sector with the DOE community. Focused advanced technology development which is sponsored by CC&AT with emphasis on joint projects with the CC&AT Team not only leads to innovative solutions to waste clean up problems but stimulates movement of technology out of the university laboratory into prototype operating systems which can be evaluated by site technologists. Innovative graduate student and faculty research is supported both by direct funding and by opening DOE Laboratory facilities to university researchers.

5. **Cooperating Multi-Arm Manipulation** -- The need for more than one dexterous manipulator to accomplish important remote tasks has been identified by many of the DOE sites as critical to successful site clean up. Examples include the manipulation of large unwieldy objects, stabilization of objects such as pipes during cutting and other size reduction operations, stabilization of long reach manipulation systems by use of one arm to grasp a stable structure in the work space, and passage of materials from one robot to another such as a gantry which may be used to transport materials over long distances. Dual arm systems are viewed as a starting point for multi-arm manipulation since many distinct tasks in remote waste clean up have been identified as requiring two arms. Operator control of multiple cooperating arms is a key area of research and automation of sensor-based operations is an important goal of CC&AT development activities. This CC&AT Major Thrust area was initiated in FY93 and is consistent with the RTDP Five Year Plan [1] which identified the need for Dual Arm manipulation technologies.

6. **Modeling and Simulation** -- The high cost and long development times required to integrate robotic systems has led to the need for advanced simulation technologies to support robot system design activities. Simulation technologies also provide the analysis tools needed to evaluate proposed robotic systems and monitor procurement activities which involve design and fabrication of new robot systems. Modeling needs include models of physical objects, geometries, the physics of interactions, dynamics, system control, etc. These models need to be highly modular and easily integrated into simulation systems. In addition, simulation systems need to be coupled with intelligent front ends which simplify their use by the non expert.

Faster, safer, cheaper operation of complex robotic systems has lead to the development of extensive computer models which capture information about the robot and its task environment (e.g., underground storage tanks, waste handling facilities, waste storage facilities, chemical analysis laboratories, old production facilities, etc.). As a result, the basic information to support an aggressive program to simulate large complex robotic applications is available. This CC&AT subtask takes advantage of existing computer models and initiates the linking of those models into an integrated simulation framework (architecture) to allow interactive simulation and analysis of advanced robotic applications. In addition, this subtask identifies new modeling needs and develops new computer models for extension of the simulation capabilities available with existing models. A critical activity within this subtask is the validation of computer models using actual operating robotic systems whenever possible. CC&AT thus couples the development of models with experimentation to validate models prior to their extensive use in design and evaluation. In addition, CC&AT develops all models in a well formalized manner so that they can be used by all members of the RTDP with minimal reprogramming and customization. It is intended that eventually, the models and simulation technologies developed within this subtask will be accessible nationwide over the evolving national information network.

7. **Technology Transfer** -- Extensive interactions with the commercial sector have led to the identification of a need for a formalized technology transfer plan for the RTDP. RTDP developed technologies enjoy widespread demand. As this

demand grows, the need for integrating technology transfer more closely with all RTDP activities grows. This subtask seeks to develop an RTDP specific Technology Transfer Plan with input directly from industry and universities where appropriate. The plan will identify opportunities and mechanisms for enhanced technology transfer, improved integration of industry/university/laboratory activities, and team based approaches to project execution where possible. Once approved CC&AT will select, with industry and university involvement, high priority projects to test implementation. A key element is involvement of the industry and university communities in all aspects of RTDP technology transfer (planning through execution) in order to get their early buy in.

DOE/INDUSTRY/UNIVERSITY FORUM

This subtask coordinates the annual RTDP DOE/Industry/University Forum in which an annual progress report, status, and new directions of RTDP activities is presented. The RTDP plans for the upcoming year are reviewed and selected technical areas are chosen for focused workshops. CC&AT sponsored technologies are demonstrated and technology transfer opportunities are explored.

REFERENCES

1. Department of Energy Environmental Restoration and Waste Management Robotics Technology Development Program: Robotics 5-Year Plan, Program Plan - Draft, September, 1990.

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