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OPERATOR-CENTERED CONTROL OF A SEMI-AUTONOMOUS INDUSTRIAL ROBOT

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This paper presents work done by Oak Ridge National Laboratory and Remotec, Inc., to develop a new operator-centered control system for Remotec's Andros telerobot. Andros robots are presently used by numerous electric utilities, the armed forces, and numerous law enforcement agencies to perform tasks which are hazardous for human operators. This project has automated task components and enhanced the video graphics display of the robot's position in the environment to significantly reduce operator workload. The procedure of automating a telerobot requires the addition of computer power to the robot, along with a variety of sensors and encoders to provide information about the robot's performance in and relationship to its environment. The resulting vehicle serves as a platform for research on strategies to integrate automated tasks with those performed by a human operator. The addition of these capabilities will greatly enhance the safety and efficiency of performance in hazardous environments.

Introduction

The robotic system described in this paper results from a cooperative effort by the Center for Engineering Systems Advanced Research (CESAR), at Oak Ridge National Laboratory (ORNL), and Remotec®, Inc., a company located in Oak Ridge, TN. CESAR, sponsored by the Engineering Sciences Program of the Department of Energy (DOE) Office of Basic Energy Sciences, represents a core long-term basic research program in intelligent machines. With support from the DOE Office of Nuclear Energy, CESAR has been performing applied robotics research, systems integration, and has provided overall coordination and management of a consortium of four university research groups (Florida, Michigan, Tennessee, Texas) in a program aimed at robotics for hazardous environments. Remotec is a world leader in research and development of remote robotic technology for hazardous operation in nuclear plants, police/military explosive ordnance disposal, and fire fighting. The company's family of robots have found a worldwide clientele, being used by several nuclear utility industries and national research laboratories to perform waste handling, surveillance, and surveying.

As delivered, the teleoperated robot requires constant monitoring of either the robot or a video screen showing the robot, or both, and the manipulation of roughly two dozen control devices on the console to control the robot. These operations place a heavy workload on the operator. Principles of operator-centered design indicate that proper design of a human-system interface should consider a number of operator-oriented issues (Norman & Draper, 1986). These include the goals and needs of the operator, the tools needed to accomplish the tasks, the kinds of tasks to be performed, and methods needed to perform those tasks. This paper describes the addition of a system of sensors, encoders and the required computing power to reduce the operator's workload by reducing the amount of monitoring required while also reducing the number and frequency of control inputs the operator must make.

All hardware and software additions are performed in a manner which preserves the factory-designed resistance of the chassis to environmental contamination, as well as the original functionality. This is desirable because the retrofitting of an enhanced control system to existing robots should require as little additional training of already skilled operators as possible.

The Andros Robot

The mobile platform of the ANDROS robot, shown in Figure 1, includes six cleated tracks, a pair of main driving tracks, and two pairs of auxiliary tracks: a pair of articulated front tracks, and an additional pair of articulated rear tracks. This unique design enables the robot to climb stairs and slopes, crawl over obstacles and ditches, make turns in tight spaces, raise the entire robot body, and maneuver

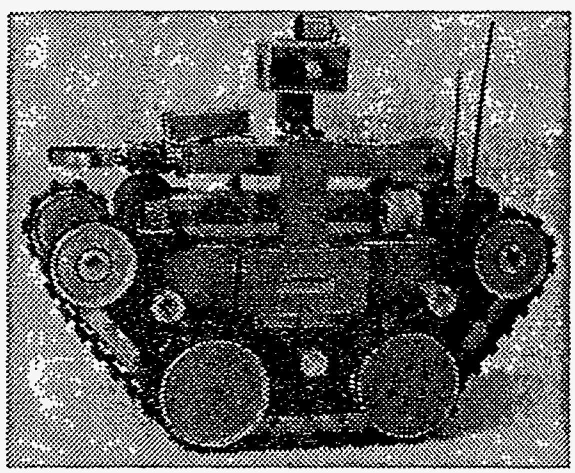

Figure 1. Remotec's Andros robot, with front and rear track articulators and the folding 5 DOF arm.

over rough terrain with different surface conditions. The ANDROS manipulator arm has five degrees-of-freedom (DOF), with a 210 degree pivot range for both shoulder and elbow. An additional DOF is provided by a torso rotation joint, in addition to the platform mobility. The wrist has pitch and six-inch extension capability, as well as continuous rotation, and the gripper has two parallel fingers controlled by servo-motors.

Two video cameras are mounted aboard the chassis: a monochrome fixed-focus camera with automatic aperture is attached to the arm, and serves as a navigation camera when the arm is parked in the home position; there is also a color camera mounted on an extendible tower with pan, tilt, zoom, and focus capabilities under operator control. This camera serves as a general surveillance camera for both navigation and manipulator arm tasks. Two-way audio communication is available through a microphone/speaker system aboard the chassis and on the console. As stated earlier, there are approximately 24 control functions on the control panel of the console, depending on what specific functions are installed on a particular Andros robot. Manipulating these control devices to smoothly control the robot and accomplish a task in the workplace requires considerable skill and practice on the part of the operator. In situations where the robot is out of direct sight of the operator, work must halt while the two cameras are used to assess current robot pose and the surrounding environment.

Workload considerations

Excessive workload on an operator of such a telerobot can degrade or slow down performance due to the number of task components which are manually performed. These components include manipulation of the cameras to monitor robot pose and tether placement, as well as to observe the effects of remote actions on the surrounding environment. In many cases, task performance must be interrupted to permit the operator to observe changes in robot pose as work progresses. The capacity to provide sensor feedback to the operator about robot position, articulator and arm position, and proximity of obstacles in the immediate environment, dramatically reduces the number of these actions required. Moreover, automation of task components requires these same kinds of sensory feedback from the environment as well as encoder feedback about the positions of various robot components.

The procedure of automating a telerobot requires the addition of computer power to the robot, along with a variety of sensors and encoders to provide information about the robot's performance in and relationship to its environment. Custom software is required to integrate the encoder and sensor information and to use this information to provide automated control input to the robot. To be most effective, a variety of tasks must be automated, including obstacle detection and avoidance, planned manipulations by the arm and end-effector, and eye-gaze control of video camera pan and tilt. Addition of these capabilities greatly enhances the tele-operation of an already successful industrial mobile robot by reducing the workload on the operator and speeding task completion.

Enhancements to the Andros robot

The factory configuration uses an RS-232 digital data link (tethered or wireless) between the console processor and the onboard control processors. Analog control actions at the console are converted into digital signals and packaged and sent to the robot where they are decoded and converted back into analog signals to control the various motors on board. This design configuration permits relatively easy addition of computing power to integrate the added functions. The additional computing power is incorporated into the robot system by means of insertion into the RS-232 data link.

One of two added processors receives incoming signals from the sensors and encoders aboard the robot. This processor interprets and stores the incoming data, updating the data tables with new sensor and encoder information as required. The second CPU serves as a monitor of the control signals generated by the operator and sent along the RS-232 link. This unique arrangement permits this processor to pass the control signals along unmodified, to alter them so as to modify the commands before they reach the control CPU in the robot, or to add new signals for automated tasks. When the monitor CPU provides no signal modification, the robot operates exactly as the factory delivered it.

Functioning of the enhanced control system

When the added control CPU functions to alter the control signals generated by the operator, it serves to move the robot from a totally teleoperated mobile robot in the direction of autonomy. Figure 2 depicts the widely accepted robotics limitation where high degrees of autonomy are attainable only in relatively simple tasks (the area under and to the left of the curve in Figure 2). The arrow pointing to the oval in the upper right indicates the direction in which we are moving with the added computing power on the Andros. As more and more task components are automated, the robot becomes more fully autonomous. With the flexibility of the present system, different degrees of autonomy can be achieved as appropriate in different task environments. Thus, the system provides a mechanism which permits research on principles and techniques for creating a symbiotic human-robot system in which automated task components are smoothly integrated with other task components performed manually.

Certain of the automated functions are planned to be permanent, while others may be invoked at some times and not at others. Many of the permanent functions fall into a class which can be designated as safety functions, and represent functions toward the lower left of the arrow in Figure 2. For example, the original robot is able to contact the pan/tilt camera tower with the manipulator arm, and it is the operator's responsibility to prevent this from occurring. With the enhanced control system in place, a software-derived envelope has been created around the camera tower, thus precluding accidental contact by the arm.

Similarly, a variety of "illegal" configurations and poses can be defined which will protect both the robot and the environment from undesirable or dangerous situations. In this capacity, the CPU which monitors the control inputs simply changes the control commands to prevent the undesirable configuration from arising. This includes stopping the robot if it attempts to navigate a slope which is too steep in either pitch or roll, or if it is about to collide with an obstacle about

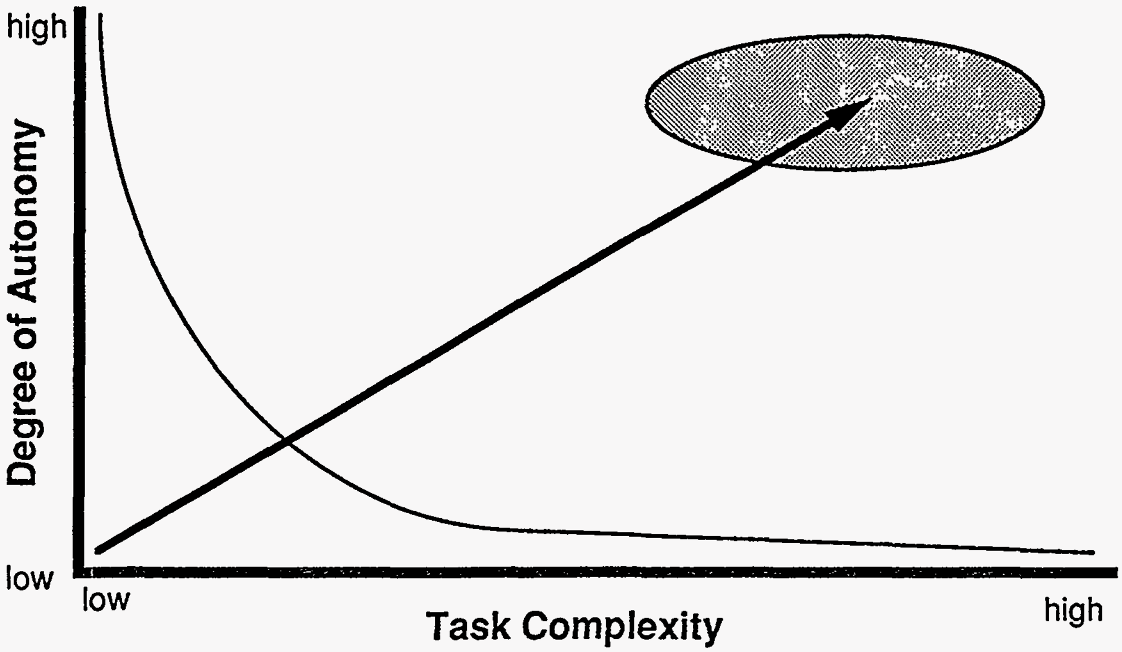

Figure 2. Diagram relating task complexity with degree of autonomy obtainable by most present-day robotic systems. The upper right oval represents the deisrable goal of high autonomy for very complex tasks.

which the operator is unaware. These types of automated functions in the robot comprise an isomorphic reflection of the numerous largely unconscious body control activities (e.g., balance, arm motions, etc.) which can be brought under deliberate conscious control when a person needs to do so. With these functions under "automatic" control, the person's conscious attention can be allocated to higher-level, more complex tasks. Similar benefits are to be expected with the automation of these low-level activities in the robot.

An example of the a situation in which such automation would help the operator is presented in Figure 3 below. This shows an Andros robot climbing a flight of stairs. In order to perform this task, the articulated front and rear tracks must be precisely positioned is such a manner that they distribute the robot's weight evenly along the entire track system. This helps to keep the robot from slipping down the stairs. In addition, the vehicle has a tendency to wander off the straight path up the staircase, and must be repositioned by the operator whenever that occurs. With the track positioning and vehicle tracking automated, the operator must merely drive the robot up the stairs using the joystick control. This automation eliminates a number of low-level monitoring and positioning tasks which the operator previously was required to do.

Other intelligent or automated capabilities might include automated obstacle negotiation, manipulator or end effector tasks, and path planning. For example, a variety of repetitive manipulator tasks such as valve turning might be automated. In this case, the operator would position the robot so it could perform the valve closing, and the additional onboard CPU would assume the responsibility for actually closing the valve. These additional automation enhancements must be planned and created on a task-by-task basis, using the principles of user-centered design. At more complex levels of task automation, greater degrees of machine autonomy become involved, as more complex tasks are performed without operator intervention.

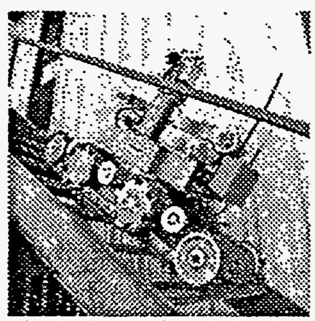

Figure 3. Andros robot climbing stairs.

Future research on operator-machine synergy

In addition to serving as the testbed for developing the enhanced control system just discussed, this prototype system provides the opportunity to experiment with the advantages and disadvantages of varying degrees of task component automation. These issues are of current interest in both aircraft cockpit automation and in the new designs of inherently safe nuclear reactor design (Spelt, 1993). Research in these areas indicates that operator boredom and takeover transients, when operator action is required, are a source of increased human error in highly automated systems.

Ultimately, this system has the capability to perform complex tasks autonomously, using sensor-based feedback from the environment. As a result, this system will serve as a research vehicle for research into the manner in which automated task components can be seamlessly integrated with operator-performed components to yield a system which is capable of functioning in hazardous environments in a way which is both safer and more efficient than can be done under full teleoperation. Neither the manner nor the degree of task automation are intuitively obvious to observers of this process. Systematic research is required, in a variety of situations, to explore the most effective ways of capitalizing on the capabilities of both the human operator and the intelligent robot.

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Operator-Centered Control of a Semiautonomous Industrial Telerobot

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OVERVIEW

- Introduction to the Andros Robot
- Description of the CRADA
- Hardware additions to Andros Mk VI for project
  - Computer power
  - Sensors & encoders
- Details of project & present status
- Video of robot

REMOTEC Andros Mk VI

- Commercial robot produced in Oak Ridge, more than 300 units fielded
- Teleoperated tracked vehicle as it comes from factory -- see viewgraph
- Milestones:
  - Demonstrate factory capabilities
  - Bring robot under computer control

DOE/ORNL CRADA with REMOTEC

- Goals:

  1. to produce a retrofitable operator interface and control enhancements

  2. explore the boundaries between teleoperation and autonomy in the robot

- Procedure: add computing power and sensors

  - New dual-CPU board developed by Remotec

  - Infrared thermography added by Remotec

- Time frame: eleven months, starting February '94

Andros Mk VI Computer Control

- Additional CPUs added -- 2 M68040s
- 6 dof KVH C100 Compass Engine
- Solid-state tilt sensors on chassis & articulators
- Encoders on:
  - Drive motor(s)**
  - Articulators
  - Manipulator motors
  - Camera pan/tilt/elevator**
- Additional sensors for range/proximity

Andros Added Computer Boards

- VME rack installed -- no "permanent" modifications to robot chassis
- Boards added
  - MVME 167 single-board computer with associated 713 I/O board
  - MVME 162 embedded controller
  - Datel DVME 613 industrial 16S (8D) channel A/D board

Other Andros Added Capabilities

- Prototype Remotec dual-CPU controller board
  - One CPU for control of system
  - Second for on-screen graphics, signal processing and factory-installed automated functions
- Wireless tether with control/audio/video
- Penney & Giles Potentiometers Ltd. CETS/300 angular position transducers -- 300º, ± 2%, 33.3 mv/º; 2 on chassis, 1 each articulator

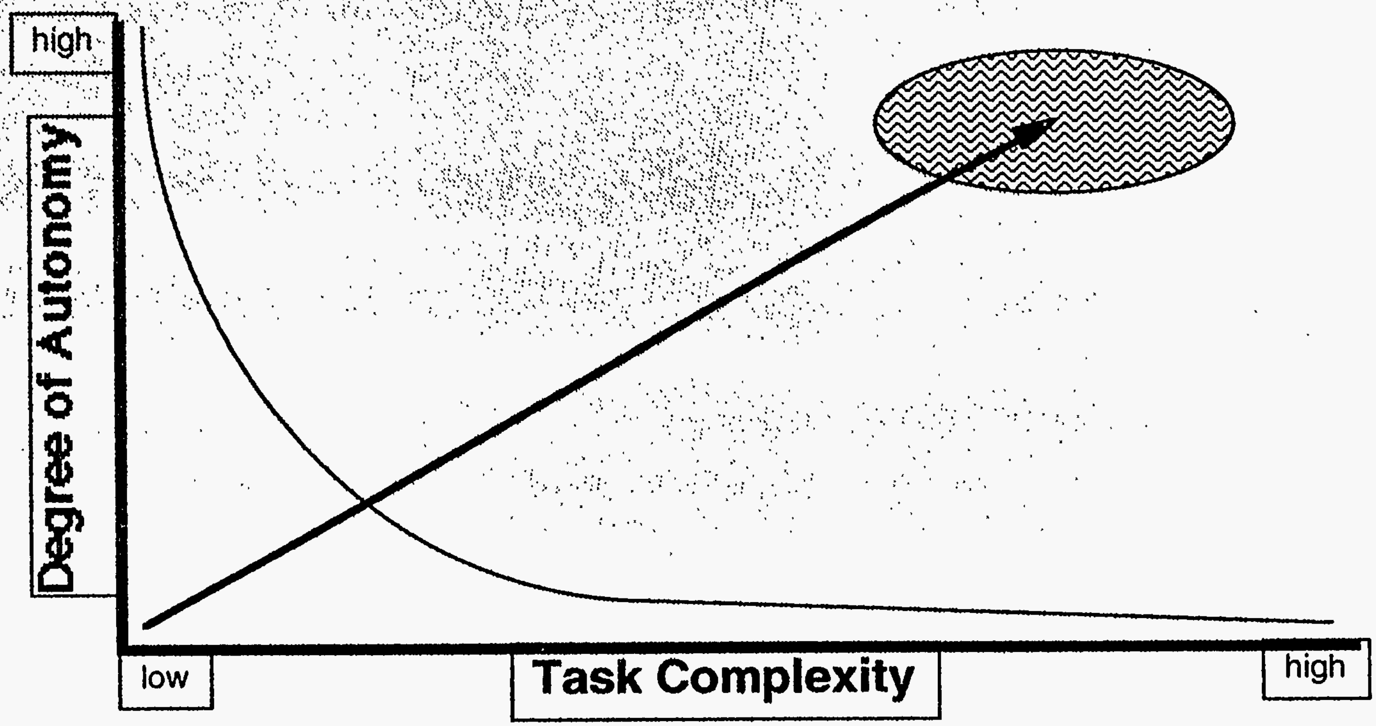
Planned Andros Sensors/Encoders

- Sealed potentiometers at all arm/camera stand joints
- Riegl USA Lasertape atop camera stand
- IR sensing capabilities
- Other capabilities as need, time & money dictate

Andros Mk VI Computer Control

- Goals:
  - Automate certain subtasks for mobility
    - Obstacle detection & avoidance
    - Stair climbing -- tracking
    - Certain manipulator subtasks
  - Eyegaze control for camera pan/tilt
- Purpose -- to reduce burden on teleoperator during complex tasks in hazardous environments

Complexity-Autonomy Tradeoff



Research Goals of CRADA

- Robot, as delivered, has 24 switches on the control pannel to control all functions
- In remote operations, operator must stop work on tasks to check on robot pose, tether position, etc.
- Addition of on-screen graphics reduces some of the operator workload
- Automation of many routine task components will further reduce workload
- Computer-enforced safety functions is also needed

Conclusions

- Work-in-progress has suffered from manufacturer delays for sensors, soon to pick up again
- A number of functions are already being planned for retrofit on fielded units, and will be included in new production models
- ORNL will have a powerful research tool at the end of the CRADA work
- A continuing relationship with Remotec has developed