A Modular Telerobot Control System for Accident Response

Robert J. Anderson and David L. Shirey
Sandia National Labs
M.S. 1125, P.O. Box 5800
Albuquerque, NM 87185

RECEIVED
AUG 18 1999
OSTI

ABSTRACT

The Accident Response Mobile Manipulator System (ARMMS) is a teleoperated emergency response vehicle that deploys two hydraulic manipulators, five cameras, and an array of sensors to the scene of an incident. It is operated from a remote base station that can be situated up to four kilometers away from the site. Recently, a modular telerobot control architecture called SMART (Sandia's Modular Architecture for Robotic and Teleoperation) was applied to ARMMS to improve the precision, safety, and operability of the manipulators on board. Using SMART, a prototype manipulator control system was developed in a couple of days, and an integrated working system was demonstrated within a couple of months. New capabilities such as camera-frame teleoperation, autonomous tool changeout and dual manipulator control have been incorporated. The final system incorporates twenty-two separate modules and implements eight different behavior modes. This paper describes the integration of SMART into the ARMMS system.

1.0 INTRODUCTION

1.1 Mission Objectives

The ARMMS vehicle system is an asset of the Department of Energy's Accident Response Group (ARG) [1]. Its primary mission is to aid in the recovery of nuclear weapons involved in accidents, but it can also respond to other emergencies, such as removing debris from a terrorist bomb site, or investigating a major nuclear and/or chemical spill. ARMMS is composed of four subsystems: a modified Highly Mobile Multipurpose Wheeled Vehicle (HMMWV) platform, two Schilling Titan II manipulator arms, a Ginchner'S-250 equipment shelter and the Operator's Control Unit (OCU).

The vehicle system is completely self-contained. It can be driven conventionally to an operation staging area, and then deployed for remote operations. Deployment consists of removing the shelter containing the OCU from the back of the vehicle, and then switching the vehicle from manned operation mode to teleoperator mode. Once converted, the ARMMS vehicle can be driven to the site of the incident using either a radio frequency (RF) modem, or a fiber optic cable communication link.

The vehicle system is designed to serve multiple purposes. It may serve as a remotely deployable camera system for investigating a site. Differential GPS tracking provides accurate tracking of the vehicle during remote operations. It may serve as a remotely deployable chemical monitoring station. A suite of hazardous gas and radiation monitoring sensors provide real-time readings from the vehicle platform. Finally, it may provide a remote manipulation capability. Two high payload, hydraulic manipulators deployed from the front of the vehicle may be used to move debris, rummage through wreckage, carry away suspect materials, and perform simple manipulation tasks. The two manipulators must be able to move objects weighing over 800 lbs, and yet be precise enough to unscrew fuse plugs on unexploded ordnance. Because of the volatile nature of the environments in which the ARMMS vehicle operates, the motion of the manipulators must be safe and steady. All of these operations must be conducted solely based on the provided camera views.

1.2 Vehicle Description

The deployment vehicle is over fifteen feet long, seven feet wide and weighs over six thousand pounds. A speed of over 50 MPH is attainable in high range and 27 MPH in low range. The foot brake, foot throttle and gear shifter are servo driven with electric actuators and variable resistance feedbacks. Steering is servo modulated with a hydraulic slave cylinder and linear potentiometer, both connected from the vehicle frame to the steering linkage.

The vehicle is outfitted with three different camera systems, with two more cameras on the manipulator arms. An on-board video switching capability makes it possible to simultaneously view any three cameras. A high-precision pan-and-

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

tilt unit controls the vehicle driving camera which is mounted above the driver cab. The second PTU camera is mounted on the hood of the vehicle, and a third fixed camera swings out on a boom from the bumper providing a side-view of operations.

The vehicle can be driven utilizing a single serial RS-232 command and control connection and a single video connection, and thus can be completely controlled in a tetherless mode utilizing the RF modems. The manipulator arms, however, require three additional lines of communication, and more simultaneous camera views, and therefore require a tethered fiber optic cable connection. A fiber optic cable spooling mechanism insures that the cable will be spooled out reliably for a distance of up to 4 KM. If the cable is severed for any reason, the vehicle can be retrieved using the RF connections and outfitted with a new fiber optic cable.

FIGURE 1: The ARMMS Vehicle System

1.3 Manipulator Description

The ARMMS manipulation capability consists of two hydraulically powered Schilling Titan II manipulators. Each arm provides six degrees of freedom plus a clamping capability. Their maximum reach from the base attachment point is 78 inches horizontally, 80 inches vertically and 270 degrees radially. To power the manipulators, a 19GPM @ 3KPSI pump is mounted on the HMMWV's diesel engine and belt driven through an electric clutch. The pump supplies power to the steering slave cylinder and the manipulator arms through a system of high pressure hoses, valves and filters. To operate, each arm requires up to 5 GPM of oil flow at 3000 PSI. The arms are bolted to a special "bumper" fabricated from 1/2" aluminum plate that can be mounted to either the front or back of the HMMWV. The hollow bumper also houses hydraulic hoses, slave electronics modules and oil filters required for the arms.

The control interface to the manipulator arms is via an on-board VME system, consisting of three 68030 processor boards, and two Schilling C30 interface boards. The VME based controller requires three RS-232 connections to the command station: one connecting to a CIS Dimension 6 spaceball; one connecting to a SGI dialbox; and the third receiving commands from the user interface on the host computer. All three of these serial channels are multiplexed using the single fiber optic connection.

FIGURE 2: The Command Station.

1.4 Command Station Description

An equipment shelter is carried to the scene of an incident in the HMMWV bed. Configured like a large pickup camper shell and measuring 70 inches high x 79 inches wide x 83 inches long, the shelter is intended to be removed at the accident site and used as a command post. A portable, 110 VAC, 5 KW, gasoline/electric generator is used to provide power to the shelter through a entrance with breaker circuits. Heavy-duty screw jacks are fixed to each corner to facilitate removal from the HMMWV. Hand-held, 12 VDC electric motors that receive power from terminals on the HMMWV speed the jack lowering and raising. The command shelter is shown in Figure 2.

Inside the shelter is the operator control unit (OCU), which contains the video display monitors, operator control computer with touch screen, flat panel command display, input devices, differential GPS base station, RF video and RF data modems, and the multi-media fiber-optic transceiver. A telescoping mast provides improved line-of-sight for both the RF antenna and an observation video camera.

1.5 Problems with Conventional Operation

The Titan manipulators on board the vehicle were originally controlled with the commercial "mini-master" controllers available from Schilling Telerobotics. The mini-masters provide a simple spatially correspondent interface to the manipulators, but made it difficult to achieve a number of the mission objectives.

First, it was difficult to grasp objects using the original interface. This was primarily a visualization problem, due to the fact that operating the spatially correspondent mini-masters required a camera view which showed the configuration of the manipulators. Both the driving camera and the hood camera were utilized while attempting grasps which were being conducted from 1-2.5 meters away from the camera. From this distance and perspective it was difficult to orient the gripper teeth with the objects to be grasped, and very difficult to accurately assess the distance to the objects.

A second problem was the possibility of inadvertent motion. During operation the operator must grasp both mini-masters. Small movements on the masters would cause large motion on the manipulators. To release a grasp on the master controllers, the operator must first tap the mini-master tool-tip to deactivate the manipulators. Unfortunately a missed tap, or an

inadvertent double tap would reactivate the manipulators. Furthermore, the operator would constantly need to re-grasp the mini-masters to reach different configurations. All of these activities resulted in unplanned motion of the manipulators and excessive fatigue for the operator trying to prevent it.

In addition a number of operations require straight-line motion, i.e., the ability to move the tip of a manipulator along a straight path or along a pre-specified arc. One example of this is tooling operations. The ability to pick up a tool from a tool rack typically requires motion along a carefully prescribed path, with straight line insertions and retractions being done to pick-up and release the tool.

Finally, to fully utilize both manipulators in a coordinated capacity it is necessary to provide lock step motion between the manipulators. Otherwise the manipulators would generate too much internal forces, lose their grasps, and drop their payloads. This coordinated motion was simply impossible to achieve with the mini-master controller interface.

2.0 SMART TECHNOLOGY

Recognizing that telerobotics tasks are often one-of-a kind operations, and that the majority of costs in deployment is directly tied to the cost of integrating these unique systems, the Robotics Center at Sandia National Laboratories has been developing technologies for rapidly developing advanced telerobotic systems. One of these technologies is SMART (Sandia's Modular Architecture for Robotics and Teleoperation) [2, 3].

SMART allows the system developer to build a multi-function telerobotic controller as a series of individual behaviors. Each behavior is made up of a set of SMART modules, where each module represents a system component, i.e., input devices, sensors, filters, constraints, and robotic mechanisms. A graphical interface called the SMART Editor is used to assemble a prototype system from a pre-existing collection of modules, represented by simple icons. The SMART Editor tests the validity of each behavior, distributes the modules over the available computing resources, and generates source code for the final system. This source code is then compiled and linked with the module libraries. The entire process for building the prototype system can be completed in hours. The SMART Editor can also generate a prototype graphic user interface (GUI), which can serve as a basis for the final system.

Using this approach, the task of building a telerobotic system is broken into a number of simpler subtasks: providing module wrappers for any new capabilities; tuning existing module parameters for the current task; and customizing a task specific graphic user interface for the end-user. As new technologies are introduced, the final system can still be rapidly reconfigured to accept the new capabilities, with minimal rewriting of the system source code.

In the case of the ARMMS vehicle system the required modules had already been written for Titan II manipulator control and for dual-arm motion control, and thus the integration tasks focused solely on hardware specific issues and user interface design. Indeed, the original design was generated and tested in a couple of days using a virtual mock-up of the manipulator system, and approximately 80% of the code used in the original system remains in use in its current implementation.

2.1 The network modelling approach.

SMART is based on non-linear, multi-dimensional networks. Each module provides a means to pass position, velocity and force information to its nearest neighbors. Each individual module can modify and transform its inputs in any way that is consistent with the concepts of passivity, and the use of independent sources. Namely, a module can generate energy into the system by means of an input device, as long as that input can be turned off at any time ($t = t_0$), and the module will only dissipate energy for any time ($t > t_0$). With these restrictions on module design it is possible to guarantee the Lyapunov stability of the continuous system based on the passivity properties of individual modules. To ensure that the stability is maintained no matter how the individual modules are sampled and connected, each module's input and output equations are mapped into wave variables before being transmitted to a neighboring module [2].

Illustrative icons are used to represent each module. The icon contains the name of the module, a graphic representation of the module and a network representation of the module. The representation used to describe the SMART modules follow the bond graph conventions of effort and flow. Force, (f) is related to voltage and velocity (v) is related to current [6]. Table 2.1 summarizes this relationship.

TABLE 2.1 Network Operators

symbol	name/ analogy	equation	symbol
M_i	inertia/inductance	$f_i = \frac{d}{dt}(M_i v_i)$
B_i	damping/ resistance	$f_i = B_i v_i$
K_i	stiffness/ capacitance	$f_i = \int K_i dx_i$
$J_{j/i}$	Jacobian/ transformer	$v_j = J_{j/i} v_i$ $f_i = J_{j/i}^T f_j$

3.0 SMART BEHAVIORS

A SMART control system is organized into a series of behaviors, each implemented by a particular combination of real-time modules. The system developer defines the modules and the behaviors that can be used in the final system using the SMART Editor and generates executables containing this set of capabilities. These executables are downloaded to the target hardware and are then available to the end-user. During operations the user will switch between the various behavior modes based upon the particular subtask being conducted. This section describes the SMART behaviors available to the user in the current implementation of the ARMMS manipulator controller.

3.1 Joint Behaviors

The simplest possible behavior for the manipulators is the ability to command joint motions. This is useful for isolating individual joint motion and for moving the robot into known configurations. The SMART behavior for executing and commanding joint motion is shown in Figure 3 below.

FIGURE 3: Joint Behavior

There are two input modules used to drive the manipulator in joint space. A trajectory generator (TRAJ module) and a dial-box interface. By combining both modules into the same behavior it is possible to use the dialbox to jog the manipulator to fixed positions, and then record the locations with the trajectory module for future playback.

The TITAN_JOINTS module maintains the interface to the robot hardware. The TITAN_JOINTS module spawns a dedicated proportional-integral-derivative (PID) control loop process that connects to the manipulator using a high-speed dedicated communication link. When the SMART system is activated, the module will stream new position commands to the PID process to generate motions, otherwise the PID loop will continually hold the robot at a fixed location.

The CONSTRAINT module insures that all motions commanded by either the trajectory generator or the dialbox are within the velocity and position constraints of the Titan II manipulator.

3.2 World Behaviors

To execute straight-line motion for the manipulator it is necessary to compute the robot's inverse kinematics. This is done with the TITAN_KIN module. Figure 4 shows how the TITAN_KIN module is used in the world behavior mode. The CIS Dimension 6 spacebar is used to command straight-line motion and pure orientation changes for the manipulator tool tip. The TITAN_KIN module translates these requests into a stream of joint data commands. Likewise, any constraints imposed by the CONSTRAINT module is reflected back to the input devices. As with the joint behavior, the input device module is used in conjunction with a trajectory module. This is particularly useful for defining the tool pick-up points needed for autonomous tool changes.

FIGURE 4: World Behavior

As with the joint behavior shown above and the tool behavior shown below there are actually two world motion behaviors ("world1" and "world2") one for each robot. The same input device is used to command either robot, but there is a separate instantiation of the TITAN_JOINTS module.

3.3 Tool Motion

By replacing the mini-master input device for the Titan with the spaceball it became possible to command smooth straight motion of the manipulator gripper. This made it possible to deploy wrist mounted cameras on the end of the manipulator arms, without a concern that they would get ripped off during normal operations. The wrist camera perspective however, proved initially difficult for the operator who was used to using the driving camera for operation, since the tool camera would have an arbitrary orientation change from the normal fixed reference point of the manipulator base. To accommodate this, a new TOOL_FRAME_KIN module was developed, to be used to aid tool frame of reference operations. It continually adjusts the input frame of reference to correspond to the manipulator tool. The tool behavior utilizing this new module dramatically improved the normal operations of the manipulator arms. (Fig 5). Tool behavior modes have been implemented for each of the two robot arms and are called "tool1" and "tool2" respectively.

FIGURE 5: Tool Behavior

3.4 Coordinated Motion

Finally, there are a number of tasks where both arms need to be controlled simultaneously. The DUAL_KIN module makes it possible for the operator to command the motion of the center grasp point of multiple manipulators. The development of

this module has been described in detail in [5]. The dual behavior utilizes this module to command the motion of both manipulators simultaneously utilizing a single input device. (Fig 6)

As with all properly designed SMART modules it is "bilateral" in nature. That is, it not only passes position and velocity information forward to the manipulator, but it also passes constraint information back to the input devices. Thus if either robot can't reach a desired location due to kinematic constraints or joint limits, this information is passed back to the input device, preventing either robot from proceeding.

FIGURE 6: "Dual" motion behavior mode.

4.0 MANIPULATOR OPERATIONS.

The operator control panel is organized in context specific pages. All standard operation commands are available using a touch-screen display. The primary display for manipulator operation is shown below (Fig 7). This interface is organized into five separate sections: specific controls for each of the two manipulators, "Titan #1" and "Titan #2"; a "VCR" type control for all trajectory generation; a camera selection section; and a SMART Command section.

The two manipulator control panels provide buttons to activate the "power-up" solenoids on each arm, and provides a slider bar to accurately control the gripper position. Each display also contains a number of large display buttons to initiate previously defined motions, such as tool pickups, dropping of objects into bins, a warm-up "dance" sequence, and a stow sequence.

Whenever any motion is initiated by touching a motion button (e.g., Move to Bin) the motion can be immediately paused, reversed and continued at a different speed by using the "VCR-like" controls. This allows the operator to monitor the motion for collisions during any semi-automatic operations. The operator can stop the motion at any time and continue with teleoperation as needed.

The SMART Command section allows the operator to determine and set the current mode of operation. Once the system is brought up into a motion-on, "activated" state, the primary operation is the selection of the current behavior. To simplify camera controls the current grid selections is also tied into the camera switching controls. Thus if an operator chooses the tool1 behavior, then the cameras will automatically switch to the wrist mounted camera on Titan #1. If the user switches to

the dual mode, then the camera switcher brings the driving camera view to the main display. Each behavior has a preferred camera view associated with it. The operator can override the default camera selection by choosing from the camera control buttons.

FIGURE 7: Manipulator Control Panel

4.1 Typical Operations

In this section two examples of typical teleoperator tasks are given: a two manipulator lifting operation and a simple bomb fuse removal. These operations each require that the operator select the operational mode from the manipulator control panel by touching the appropriate button, and then adjusting the input devices based on the camera feedback.

First, to perform a two-manipulator lift the object needs to be grasped by one of the robots, e.g., Titan #1. The operator will start with behavior **world1**, and teleoperate the robot close to a reasonable grasp point based on the driving camera view. Once the robot is close enough to the object that the wrist camera can view the desired grasp location, the operator will then select **tool1** view and approach and align to the grasp point using the wrist mounted camera. Once the gripper is aligned, the operator can command gripper closure using the robot specific display for Titan#1. To grasp the common object with the second robot the same sequence is repeated using the behaviors **world2** and **tool2**, and the robot specific display for Titan#2. Finally, once the object is grasped by both objects, the user can choose the **dual** behavior mode to lift and manipulator the object from a common reference frame. Once lifted, the vehicle can be driven away holding the retrieved object.

To perform a bomb fuse removal task the second robot will be used to steady and fixture the bomb, while the first robot unscrews the bomb fuse. To move to the bomb and hold it in a accessible position, the operator utilizes the **world2** behavior, until the bomb is securely grasped. Once the object is held by the second robot, the operator then moves the first robot into place first with the **world1** behavior, and then with the **tool1** behavior to get close alignment with the tool axis of the

manipulator. Once grasped the operator can either unscrew the bomb fuse by switching to **joint1** mode and moving just the sixth joint of the manipulator, or staying in **tool1** mode and using the dominant mode of the space ball to isolate the single axis of motion. Once the fuse is removed, selecting the "Move To Bin" button will cause the manipulator to drop the retrieved fuse into a predefined bin location attached to the vehicle.

5.0 CONCLUSIONS

The use of SMART on the ARMMS vehicle system has substantially improved the system's base capability. Operations that were once difficult to achieve using the conventional interface, are now conducted routinely and reliably. Inadvertent motions have been essentially eliminated, and the operator has been able to demonstrate coordinated behavior of the two manipulators, e.g., lifting and retrieving a 800 lb. bomb mock-up by utilizing both arms. Although the interface requires that the operator constantly specify changes in behavior modes by selecting options on the touch-screen, this has been deemed a small price to pay for the increased safety and operability of the system.

6.0 ACKNOWLEDGEMENTS

This work was performed at Sandia National Laboratories, operated for the U.S. Department of Energy under contract number DE-AC04-94-AL85000.

7.0 REFERENCES

1. W. D. Morse, D. L. Shirey, R. J. Anderson, D. CdeBaca, D. R. Hayward, S. D. Spray, "Accident Response Mobile Manipulation and Hazard Sensing", '99 ANS *Proceedings of the Eighth International Topical Meeting on Robotic and Remote Systems*, Pittsburgh, PA, May. 99.
2. R. J. Anderson, "SMART: A Modular Control Architecture for Telerobotics", *IEEE Robotics and Automation Society Magazine*, pp. 10-18, Sept. 95.
3. R. J. Anderson, "A Modular Approach to Robot Control", '96 *IEEE International Conference on Robotics and Automation*, St. Paul, Minn., pp. 699-705.
4. R. J. Anderson, "A Modular Approach to Sensor Integration," *Control in Robotics and Automation: Sensor-Based Integration* edited by B.K. Ghosh, Ning Xi, and T. J. Tarn, Academic Press, pp. 245-268, 1999
5. R. J. Anderson and K. Lilly, "A modular approach to multi-robot control". *Proceedings of the 34th Conference on Decision & Control*, New Orleans, Dec. 1995, pp. 1021-1027.
6. R. Rosenberg, and D. Karnopp, *Introduction to Physical System Dynamics*, McGraw-Hill, New York, 1983.