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Reconfigurable Mobile Manipulation for Accident Response

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Abstract

The need for a telerobotic vehicle with hazard sensing and integral manipulation capabilities has been identified for use in transportation accidents where nuclear weapons are involved. The Accident Response Mobile Manipulation System (ARMMS) platform has been developed to provide remote dexterous manipulation and hazard sensing for the Accident Response Group (ARG) at Sandia National Laboratories. The ARMMS' mobility platform is a military HMMWV that is teleoperated over RF or Fiber Optic communication channels. ARMMS is equipped with two high strength Schilling Titan II manipulators and a suite of hazardous gas and radiation sensors. Recently, a modular telerobotic control architecture call SMART (Sandia Modular Architecture for Robotic and Teleoperation) has been applied to ARMMS. SMART enables input devices and many system behaviors to be rapidly configured in the field for specific mission needs. This paper summarizes current SMART developments applied to ARMMS.

1.0 Introduction

The Accident Response Group (ARG) is a multi-organizational team responsible for responding to accidents involving nuclear weapons. ARG capabilities require the performance of complex technical tasks in environmental conditions that might include radiological hazards, gas and chemical hazards, inclement weather and difficult terrain. Shown in Figure 1, the Accident Response Mobile Manipulation System (ARMMS) has been developed to reduce exposure of response team personnel to these hazards through telerobotic mobile manipulation (Morse 1994). The platform uses the military's High Mobility Multipurpose Wheeled Vehicle (HMMWV) configured with two high strength Schilling Titan II manipulators with a reach to separation ratio of 1.34 that closely approximates a human's 1.26 ratio (Woodson 1992). The Ginchner S-250 shelter, shown in Figure 2, serves as the ARMMS Command and Control Shelter (CCS) where remote operations are conducted. ARMMS is completely self-contained. It can be driven conventionally to an operations staging area, and then deployed for remote operations. Deployment consists of removing the CSS from the back of the HMMWV, and switching the vehicle from manned operation mode to telerobotics mode. Once converted, ARMMS can be driven to the accident site using either radio frequency or fiber optic communication links. The vehicle system is

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designed to serve multiple purposes: remote visual inspections, site GPS mapping, chemical and hazardous gas monitoring, radiological monitoring, and remote dextrous manipulation functions. The ARMMS manipulators must be capable of gently moving objects weighing hundreds of pounds and yet still have the precision and coordination to unscrew fuse plugs on unexploded ordnance. Because of the nature of the environments in which ARMMS operates, the motion of the manipulators must be both safe and steady.

Figure 1. Accident Response Mobile Manipulation System (ARMMS) front view showing its dual Schilling Titan 2 manipulators and ARMMS removing a trainer bomb (see in red) from a simulated F-4 crash site.

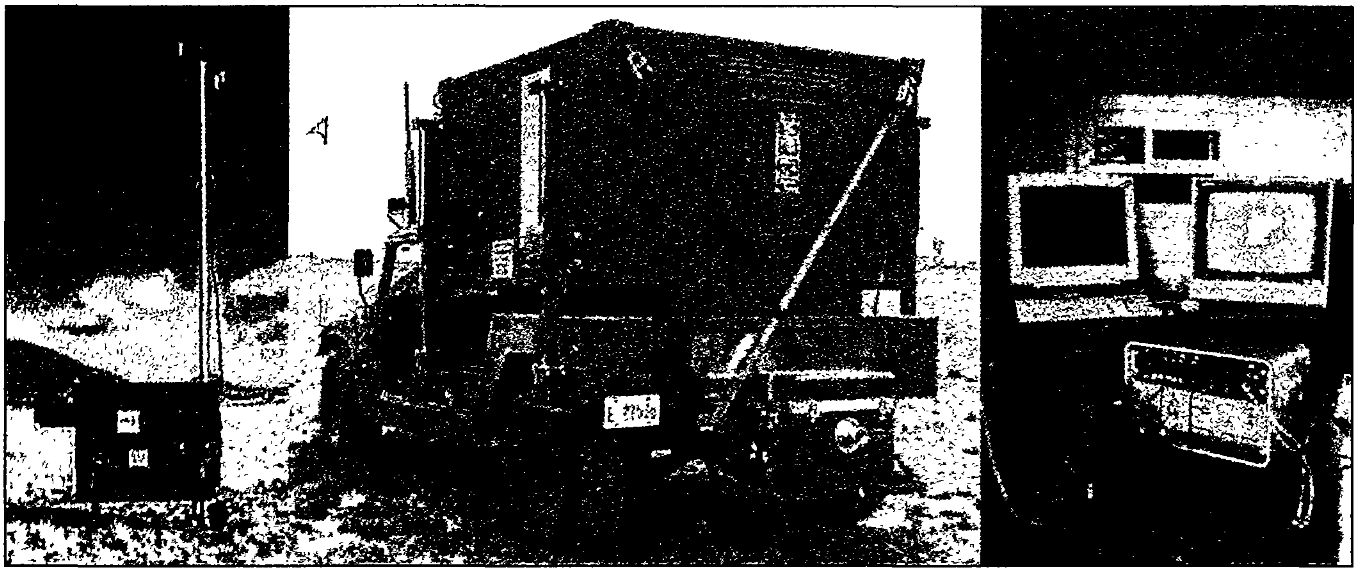

Figure 2. ARMMS Command and Control Shelter (CCS) is first shown deployed standing on its integral jack stands with the pneumatic mask holding antennae and observation camera fully hoisted. Shown from the rear is the CCS secured to the HMMWV bed with the fiber optic cable dispenser also visible. The interior of the CCS is shown on the far right.

2.0 The Need for Reconfigurable Coordinated Telerobotic Multiple Manipulation

Early ARMMS performance characterization testing (Morse 1995) identified many operational limitations and established a baseline against which to compare future enhancements. Figure 3 shows one of these early test configurations with ARMMS sporting a pair of Schilling Titan 7F manipulators. The manipulators were controlled using Schilling's mini-master spatially correspondent controllers and various video perspectives were employed that included stereo vision. The testing involved the lifting and manipulation of a ponderous W80 weapon container using various tool attachments. It was expected and quickly observed that simultaneous dual arm operations were very difficult to conduct and resulted in frequent failures when trying to coordinate both arms in heavy large mass lift operations. Additional dexterous single arm operations, such as nut and bolt removal from the W80 container-locking ring, were also performed and resulted in rapid operator fatigue and frequent attempt failures.

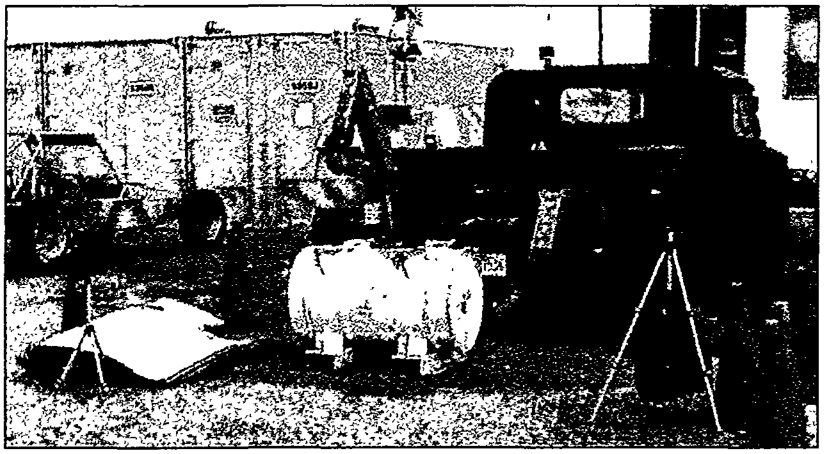

Figure 3. Early ARMMS performance characterization testing using dual Schilling Titan 7F manipulator to lift a W80 shipping container.

It was recognized early on that telerobotic tasks are often one-of-a-kind operations and that the major cost associated with the successful deployment of robotic systems was for the integration of tools, sensors, and other subsystems. Sandia controls and software research has resulted in technology developments that enable rapid robotic system reconfiguration and subsystem integration to address these deterring cost issues. One specific control and integration tool that has been applied to ARMMS is the patented Sandia Modular Architecture for Robotics and Teleoperation (SMART) (Anderson 1996c). SMART addresses many of the difficulties associated with both frequent reconfiguration and coordinated mobile multiple manipulation: lifecycle costs, operator training, operator fatigue, inadvertent motion, straight line motion, lock step coordinated dual manipulator motion, unplanned contacts, and so on.

To evaluate enhanced operational capabilities resulting from the incorporation of SMART into ARMMS a series of tests utilizing a heavy B61 bomb trainer were conducted. The testing required ARMMS to first lift, rotate, and position the B61 to gain access to lifting lug thread inserts. Lifting lugs were then remotely screwed into the inserts by ARMMS. Custom fabricated lifting tools were then grasped and inserted into the lifting lugs as shown in Figure 4. The operator, using a single spaceball input device, proceeded to successfully lift the bomb trainer also shown in Figure 4. The operator workload previously associated with coordinating the arms for heavy large mass lifts was now totally transparent to the operator. Once hoisted, ARMMS backed the B61 away from the wreckage and then gently lowered it to the ground to conduct further inspections and operations. Completing this operational test scenario was previously not possible using spatially correspondent input controllers.

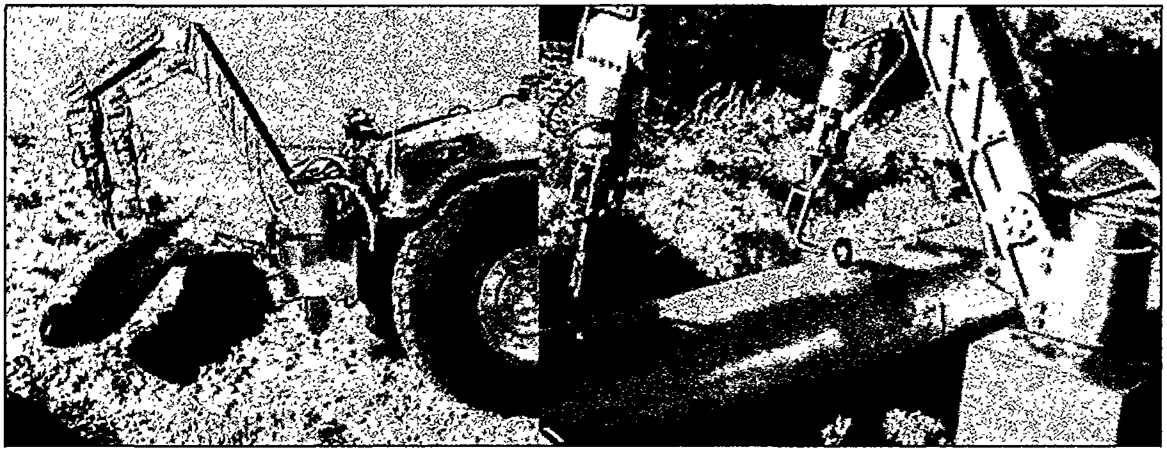

Figure 4. ARMMS using coordinated manipulation to lift a B61 bomb trainer.

3.0 Sandia Modular Architecture for Robotics and Teleoperation (SMART)

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 prototype systems 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 graphical 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 graphical 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 the required modules had already been written for Titan II manipulator control and for dual-arm motion control, and thus the integration task 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.

3.1 The Network Modeling 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 produce energy into the system by means of an input device, as long as that input can be turned off at any time ($t=t_o$), and the module will only dissipate energy for any time ($t>t_o$). 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 (Slotine 1997)

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_i) is related to voltage and velocity (v_i) is related to current (Rosenberg 1983).

4.0 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 SMART onboard ARMMS.

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 4.

There are two input modules used to drive the manipulator in joint space. A trajectory generator (TRAJ module) and a dialbox 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 TITAM_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 communications 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.

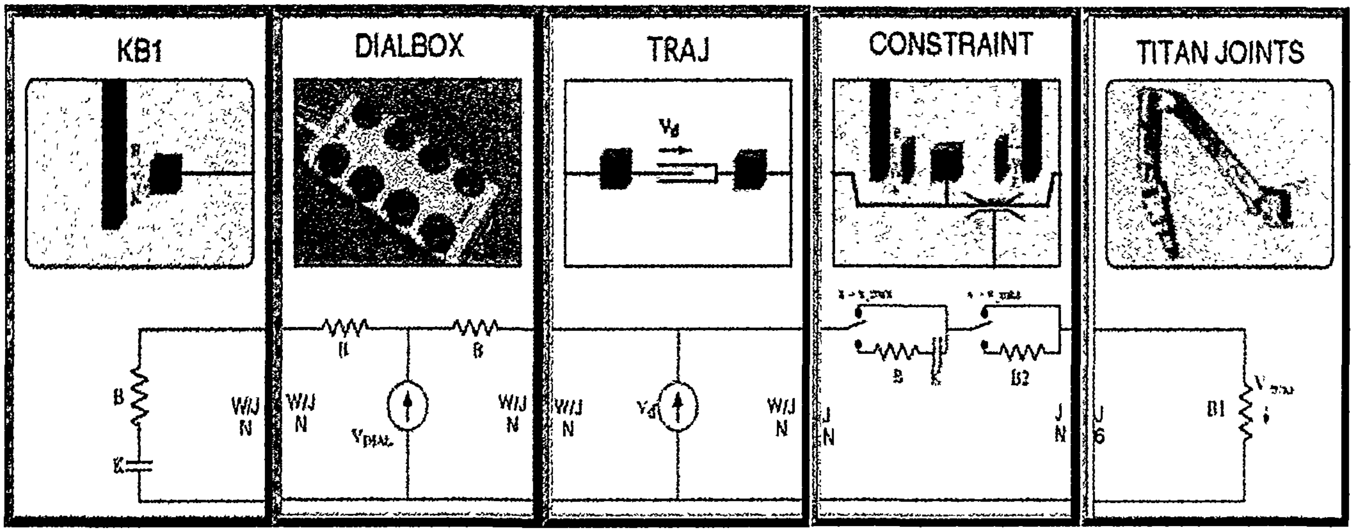

Figure 4. SMART Editor; Joint Behavior

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 5 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 TIAN_KIN module translates these requests into a stream of joint data commands. Likewise, any constraint 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. 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.

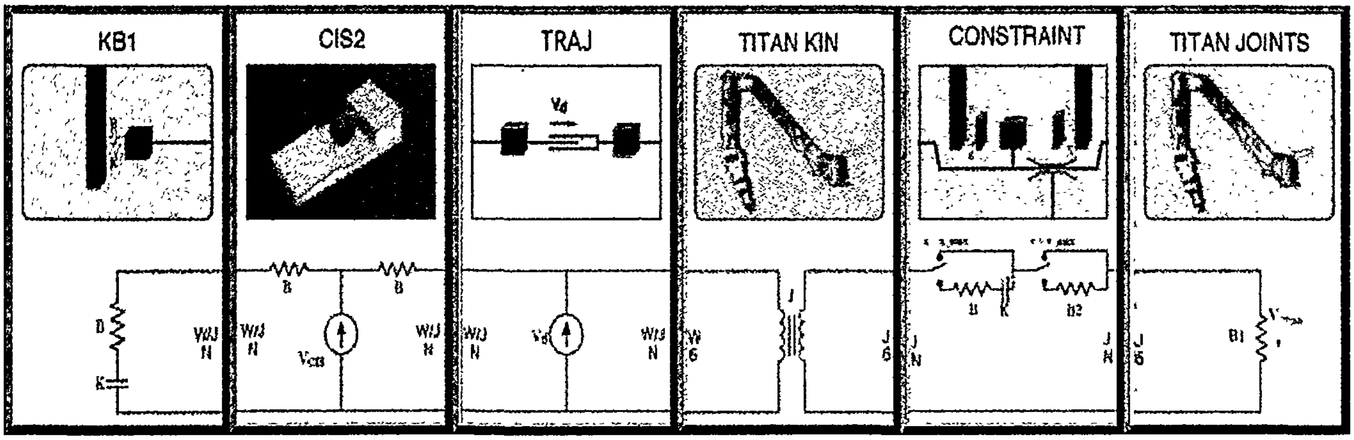

Figure 5. SMART Editor; World Behavior

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. Tool behavior modes have been implemented for each of the two robot arms and are called "**tool1**" and "**tool2**" respectively and shown Figure 6.

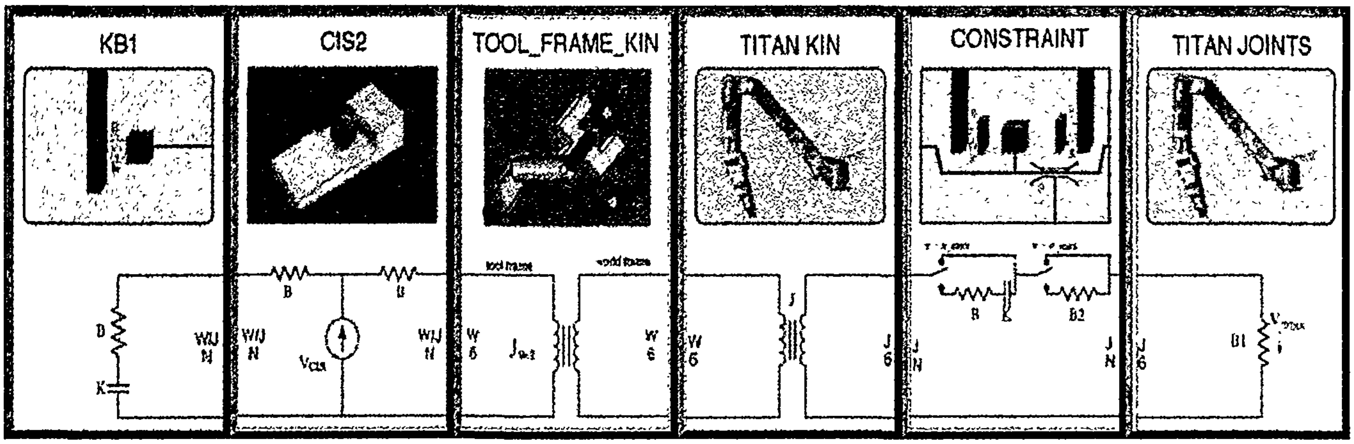

Figure 6. SMART Editor; Tool Behavior

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 (Anderson 1995). The dual behavior utilizes this module to command the motion of both manipulators simultaneously utilizing a single input device and is shown in Figure 7. As with all properly designed SMART modules it is "bilateral" in nature. This 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 not 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.

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 in (FIGURE Manipulator control panel). 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 generations: 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" control. This allows the operator to monitor the motion for collisions during any semi-autonomic 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 "activate" 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 tooll 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 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.

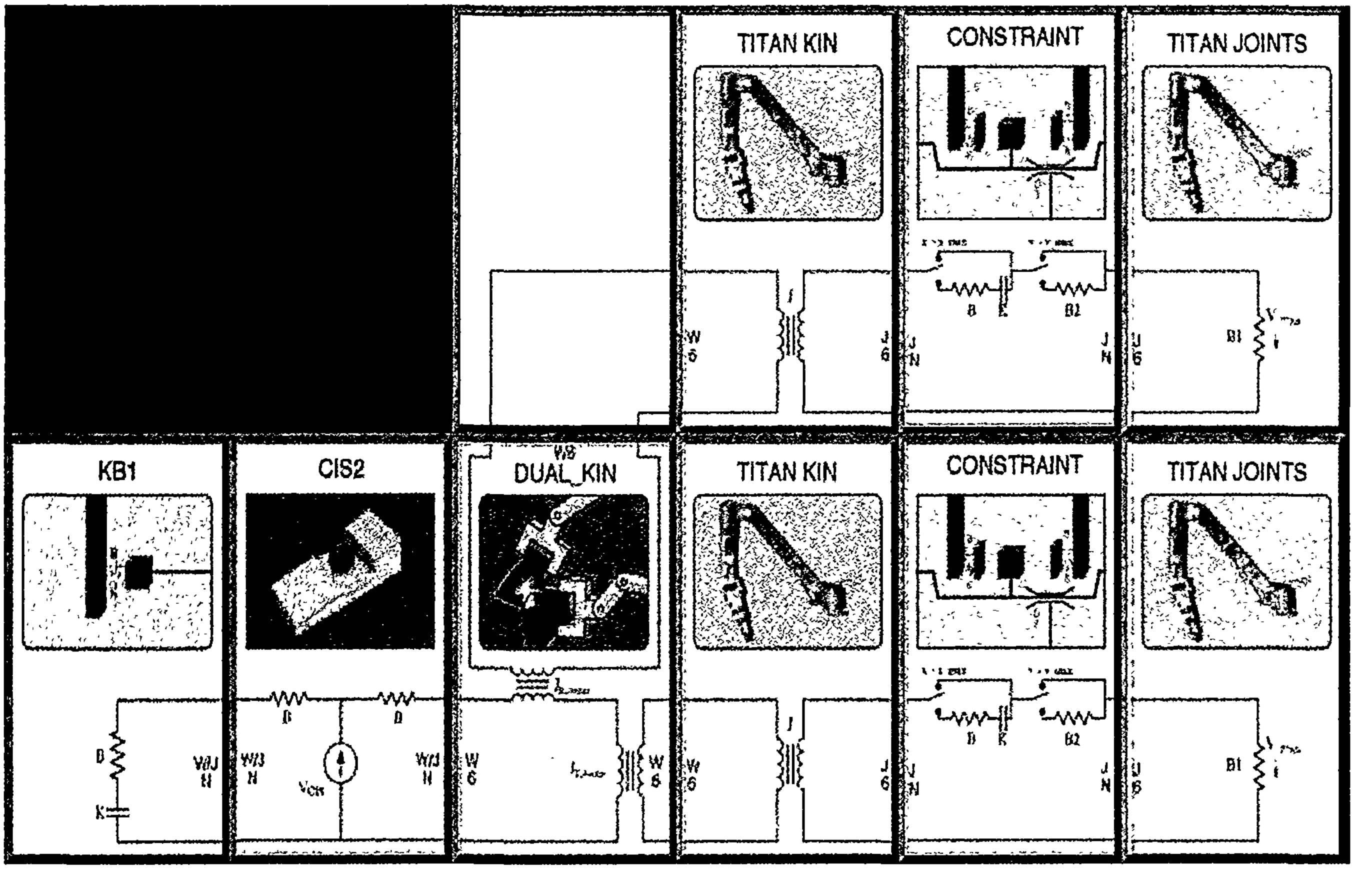

Figure 7. SMART Editor; Tool Behavior

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 to 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 manipulate 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 an 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 spaceball 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

ARMMS has matured to a robust advanced remote manipulation and hazard-sensing platform. Significant operational enhancements have been realized as compared with the original configuration by the incorporation of SMART. Operations that were once difficult to achieve are now conducted routinely and reliably. Indadvertent motions have been eliminated, and the operator has been able to deomstrate coordinated behaviors of two manipulators. Future plans for ARMMS include the implementation of coordinated vehicle and manipulator control and advanced user interfaces.

Acknowledgements

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