# Recent Telerobotics Systems Developments at the University of Tennessee

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**Abstract** – *Current efforts in the University of Tennessee at Knoxville robotics laboratory include expanding the existing Robot Task Space Analyzer (RTSA) to a dual arm system and integration of a new sensor head, implementation of the Barrett Whole Arm Maniplator as a universal master controller, and integration of the Barrett Wraptor multi-fingered end-effector to a Schilling Titan II hydraulic manipulator. This paper provides a survey of the vision for the RTSA, outlines the research issues behind the project topics, and identifies at a high level the technical solutions for implementation.*

## I. INTRODUCTION

The Robot Task Space Analyzer (RTSA) has been the focal point of robotics and remote systems research at the University of Tennessee at Knoxville since the late 1990s. This work originally started with a single manipulator and stereo vision-based sensor head. Currently two Schilling Titan II hydraulic manipulators are mounted on a cross bar pedestal with a new sensor head mounted in between the two arms on the pedestal. The sensor head, which contains both stereo cameras and a laser rangefinder, is used to generate task models in the robot workspace that the robot manipulators can then execute autonomously. The right manipulator has the standard Schilling parallel jaw gripper. The left manipulator has been modified to mount the Barrett Wraptor multi-fingered end-effector. A standard Schilling minimaster controller is connected to the right manipulator; a newly developed master controller version of the Barrett Whole Arm Manipulator (WAM) has been integrated into a compact remote console (CRC) supplied by Oak Ridge National Laboratory (ORNL) and is tied to the left arm control system. Therefore the right arm of the dual arm system provides conventional manipulator technology while the left arm supplies more advanced articulation and grasping capabilities. This provides the capability for comparative studies between conventional vs. enhanced control. Since the WAM is a 7 degree-of-freedom (DOF) manipulator and the Schilling is a 6 DOF manipulator, the WAM redundant DOF must be managed and the teleoperation control algorithm completed in Cartesian rather than joint level control. One key problem for sensor-based telerobotics is getting the manipulator to accurately grasp the object targeted by the sensor head. This led to a serious study of robot and sensor calibration issues.

## II. RTSA HISTORY AND PROGRESS TO DATE

The Robot Task Space Analyzer (RTSA) concept grew out of the task space scene analysis (TSSA) work proposed by Hamel and first tested at ORNL in the mid 90s. Up to that time, most model-based robotic task execution had involved the use of a priori generation of world models, typically generated by hand which required long periods of time to generate even for relatively simple models. The Department of Energy Environmental Management sponsor, the Deactivation and Decommissioning (D&D) Focus Area, required operations in complex unstructured environments that were constantly changing as equipment was removed. A priori models were clearly not sufficient since the environment changed continuously. Long model generation times were not acceptable for efficient operations. Therefore sensor-based task-oriented modeling that incrementally modeled the task at hand, executed that task, and then moved on to generate a new task model-robot execution pair seemed most reasonable. The TSSA sensor head used stereo vision only and was mounted on a high precision pan/tilt mechanism that was in turn mounted on the ORNL dual arm work module (DAWM). The TSSA was used to model the location of a section of process tubing that was in turn cut via automated robot task execution by the DAWM using a hydraulic shear moved to the location specified by the TSSA system [1]. While the proof of concept demonstration was successful, it was determined that more research was necessary before a product could move to the field, and so the work was moved to University of Tennessee at Knoxville (UTK) where it became the RTSA project.

Automated dismantlement tasks require reasoning about the 3D structure of the task environment and planning for the motion and actuation of robots and tools.

It therefore requires quantitative position, size, and shape information about equipment to be dismantled and other objects surrounding it that the robot needs to have knowledge of. The RTSA is one system by which the necessary geometric data is acquired, processed, and integrated [2,3]. The position of the equipment is also needed to plan collision-free robot motions, though it may not be necessary to make a detailed analysis of their geometry (i.e., the existence/absence of solid matter at a point in space is all that is necessary). RTSA results, or models, must be complete and accurate to the extent dictated by the specific tool being used: positioning of a shear demands less accuracy than maintaining the proper standoff for a plasma arc torch. Once an appropriate model is available, algorithms to plan manipulator trajectories and tooling motions can be applied, and the cutting can be automatically executed.

The RTSA has three major scene analysis components (i.e., manual, stereo auto-scanning and range auto-scanning) as shown in Figure 1. The manual modeling utilities allow the operator to select three-dimensional coordinate points with the laser range finder on the sensor head to define part positions. To use either the stereo AutoScan or the range AutoScan module, the operator first selects a region of interest (ROI) from a panoramic view (PV) of the task scene. Using the graphical user interface, one of the AutoScan modules is then selected, and then one or more classes of objects to be found in the ROI is specified in the catalog of object primitives or object of interest (OOI). In its current implementation, RTSA contains object classes for standardized process piping components (valves and elbows, Tees and other unions) and a custom object tool. The operator must also specify the schedule and size of the object and whether it is welded, flanged, or bolted.

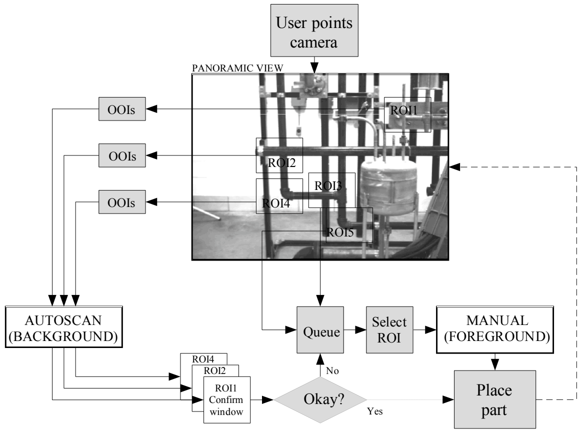

Fig. 1. RTSA major functional components.

The structure of the RTSA combines interactive analysis of objects that can be modeled with relatively simple descriptions and operator specifications (e.g., pipe sections and elbows) with automatic analysis of scene objects that have more complicated descriptions (e.g., valves). With three paths available for the analysis of the task space, the operator is both an administrator and an active participant. Regardless of the method used to locate a particular object in the scene, the operator makes final approval of the object placement. The operator also has the option to make small adjustments in translation and rotation of the object as it appears in the task space model.

Once the objects to be removed have been identified and modeled, a task script is generated and a path planned for download to the robot controller. Tasks demonstrated to date at UTK have primarily focused on the use of a manipulator held portable band-saw to remove sections of process piping from a mockup.

## III. RTSA HARDWARE

Excluding sensor systems and support, the RTSA controls reside on two PC-compatible personal computers. The first is a Windows-based dual processor machine that is used for the RTSA front end and the associated image processing (each run on a separate processor). Additional commercial cards required include an image processing card and 4-port serial card (due to a large number of serial-based peripherals used in the RTSA external support hardware). The second computer system in the UTK RTSA system is a linux-based machine that runs the Real-Time Innovations, Inc., ControlShell software development environment and run-time architecture for the high-level robotics functions. The same system runs the open source linux-based real-time application interface (RTAI) real-time linux kernel for the low level controls. The linux machine provides all of the UTK low-level control and robotics functions.

The original RTSA system used a single Schilling Titan II manipulator. The test-bed has been expanded to a dual arm Titan II system. Currently the controls are hybrid during final transition to a working integrated system. On the right arm, the existing linux machine connects to a Schilling Titan 2 hydraulic manipulator via a bus repeater, VME interface rack, and Schilling's VME controller interface. On the left arm, the Titan II is interfaced to its PC controller via the ORNL-developed PC/104 low-level controller, shown in Figure 2. The ORNL controller, which is in use at several national laboratories, runs the QNX operating system and is capable of interfacing either to computer control for robotics or to the standard Schilling mini-master controller for teleoperation. Currently the left arm is controlled via a separate PC via the WAM master controller; however future plans include the use of dual PC/104 controllers, one for each arm feed into a single linux-based computer running a dual arm RTSA as shown in Figure 3. The original VME controller will be removed, and controls will be consolidated as much as practical, though it is possible that more PCs will have to be used given the intensity of the control functions. Part of the reason for the current separation is that the two arms are currently being used for separate functions and development efforts with separate goals. This will be discussed in more detail in a later section.

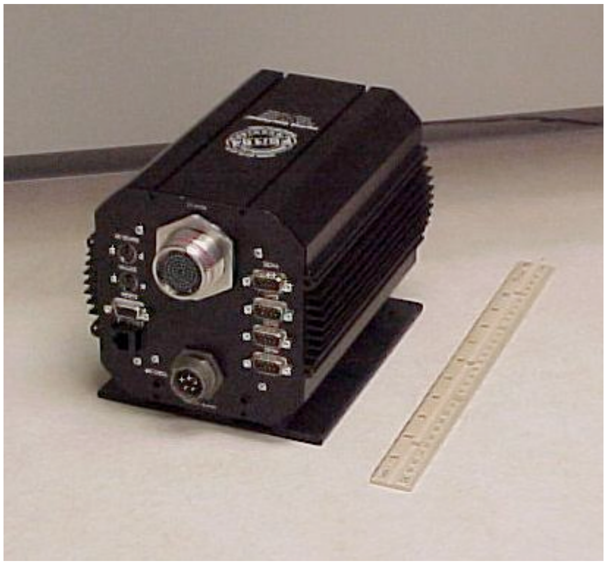

Fig. 2. PC/104 controller.

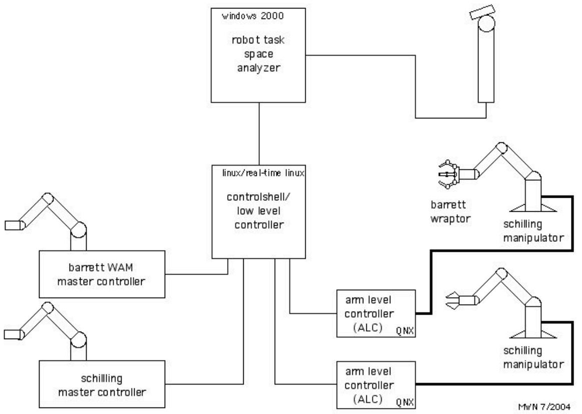

Fig. 3. Dual arm RTSA high level architecture.

The original TSSA sensor head has been replaced with a new custom unit designed and built by UTK. The new sensor system provides both stereo imaging capability and a laser rangefinder; however the current RTSA implementation uses a single camera channel in combination with the laser rangefinder as it appears to be a more accurate than stereo imaging. The camera and laser rangefinder sensor system is mounted on a precision pan & tilt unit in turn mounted on a pedestal on top of the dual arm manipulator system cross beam shown in Figure 4. For a sensor-based robotics system to work effectively, it is essential that the sensor head and robot be properly calibrated. Extensive testing, measurement, and development have been completed for this system to calibrate, verify, and improve the sensing and position accuracies to the maximum possible given the hardware available [4].

Fig. 4. Dual arm manipulator with calibration fixturing on the right arm, sensor head, and calibration array.

A calibration board with an array of feducial markers (also shown in Figure 4) was fabricated and set up in the robot workspace. Feducial markers were also placed on the sensor head and custom fabricated calibration fixturing for the robot manipulator. Data was collected using the sensor head for the calibration board and the robot manipulator. Calibration data was then collected using a Pentax Total Station (surveying instrument) as a known standard. Calibration of the sensor head was successful to within 5mm at the 2m working distance of the manipulators. This defines the degree of accuracy and the type of tasks that RTSA is capable of executing. Calibration of the Schilling manipulator and integration of the calibration results into the existing controller is still in progress.

## IV. DEXTROUS TELEOPERATION

While there are plans to integrate the left manipulator into the overall RTSA system as an integrated dual arm system, it is currently being used to support development of dextrous teleoperation based on the use of a Barrett multi-finger end-effector, the Wraptor shown in Figure 5, to replace the standard Schilling parallel jaw gripper and a Barrett 7 DOF version of their WAM manipulator as a master controller. There are both significant advantages and challenges to this configuration [5].

Tooling for use by manipulators with parallel jaw grippers generally needs to be custom modified for grasping as show by the band saw in Figure 6. These fixtures are typically bulky and unnatural for hand-held use. When a tool breaks (a common occurrence in D&D-type operations), the fixturing must be moved to or replicated for the new replacement tooling. The Wraptor, a three-fingered (actually configured as one finger and two thumbs that can be rotated 180°) end-effector is capable of human-like grasp on objects of "natural" shapes such as tool handles without the need for additional fixturing. The only caveat is that the Wraptor is designed as a heavy-duty hand and is therefore significantly larger than the human hand, i.e. small tools are sometimes difficult to grasp. In Figure 4, the Wraptor is shown grasping a handheld reciprocating saw that is large enough that a human operator would normally hold it with both hands. Issues with the use of a multi-finger end-effector include how to integrate a controller into an existing arm level master controller and how to actual manage the complex grasping motion of the hand without burdening the operator such that it impedes rather than enhances teleoperation.

Full-scale positional master controllers provide the operator with a sense of corresponding motion from their hand/arm motion to that of the manipulator that they are viewing through the remote viewing system. Mini-master systems are often used because they are cheaper and require less space. They often also cause less overall fatigue during the remote operation. However, mini-masters also limit the operator's resolution of motion and ability to do fine tasks. Typically positional master controllers must be custom-made to match the kinematics of the manipulator that they are used to control (the cost factor); joint level control is used. Given that a large-scale positional master controller is desirable under certain circumstances, it would be advantageous to have a generic master controller that would support a wide range of manipulator designs so that cost would not be so great an issue. However, there is then the issue of non-correspondence between the master and the manipulator. This is addressed with Cartesian control via the use of forward and inverse kinematics to manage positioning of the manipulator by the master controller and force feedback to the master controller. Additional complexities are added by the existence of the redundant kinematics of the master controller (the WAM is 7 DOF; the Schilling and most manipulators are 6 DOF). The redundant degree of freedom must be driven such that it does not interfere with the operator in any way.

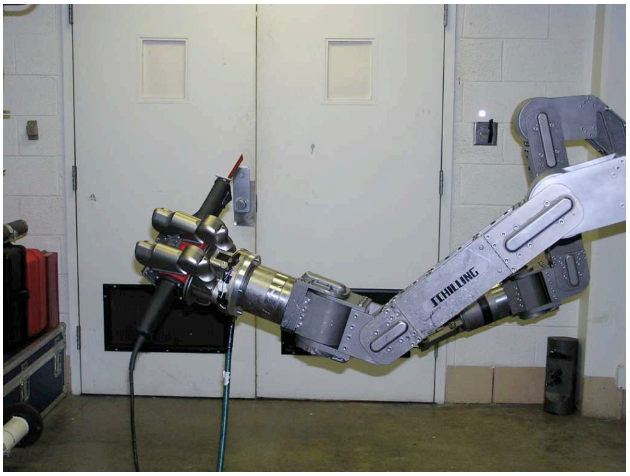

Fig. 5. Barrett Wraptor hand integrated to the Schilling Titan II hydraulic manipulator.

Fig. 6. Handheld band saw modified for parallel gripper use.

For efficient operation, any master controller should be integrated into a human factors-based operator console. The UTK team chose to use an available compact remote console (CRC) prototyped by ORNL but now commercially available from Agile Engineering, Knoxville, TN. The CRC, shown in Figure 7, compresses a control room's worth of operator station—remote viewing and function control—down to a portable chair-based system that can be moved through a regular doorway, unfolded, and quickly set up. Flat panel video screens and graphics monitors are mounted in an adjustable array in front of the operator. Computer controls are placed in easily accessed positions around the console's seating position. It is designed such that a wide array of manipulator and mobile platform master controllers may be integrated into the system design. Since the WAM is larger than most master controllers normally used with the CRC, an easily removable carriage was designed to mount on the side of the CRC. The WAM was then mounted to this carriage. Figure 8 shows a hypothetical arrangement for a dual WAM-based master controller system for a generic dual arm manipulator system.

Fig. 7. Compact remote console.

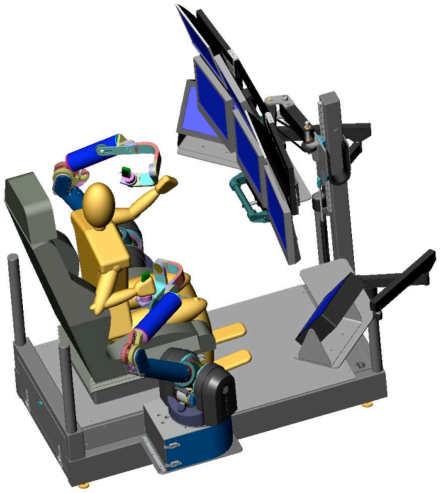

Fig. 8. A hypothetical dual WAM-based master control system.

Implementation of the controls algorithms in support of the WAM master—Schilling manipulator architecture is currently in progress

## V. CONCLUSIONS AND FUTURE WORK

RTSA is moving towards a culmination in a sensor-based dual arm telerobotic system accurate enough to manage tasks with a 5mm resolution. The task focus is incremental and model generation is on line such that there is minimal a priori modeling. In addition, issues related to dextrous grasping are being worked by the integration of a multi-fingered end-effector. Efficiency of teleoperation is being worked by the integration of a generic full-scale master controller with redundant DOF to allow for positioning per comfort and preference of the operator. Integration of all of this capability into a single system is a formidable task. Issues as diverse as integration into an ergonomic operator station and calibration of sensor and manipulator systems must be coordinated and worked into the overall picture.

Significant progress to date has been made on control of the Barrett hand, calibration of the sensor head system, integration of the PC/104 controller and the linux-based controller for the WAM manipulator. However, much additional work needs to be completed to tie all systems capability into one working system. The WAM algorithms for management of the redundant DOF and to implement generic Cartesian master control must be implemented. A joystick controller for the Wraptor must also be integrated. The final most significant integration activity will be to fold in the dextrous manipulation capability to a dual arm RTSA system.

## ACKNOWLEDGMENTS

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