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Multi-Robots to Micro-Surgery: Selected Robotic Applications at Sandia National Laboratories*

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The Intelligent Systems and Robotics Center (ISRC) at Sandia National Laboratories is a multi-program organization, pursuing research, development and applications in a wide range of fields. Activities range from large-scale applications such as nuclear facility dismantlement for the United States Department of Energy (DOE), to aircraft inspection and refurbishment, to automated script and program generation for robotic manufacturing and assembly, to miniature robotic devices and sensors for remote sensing and micro-surgery. This paper describes six activities in the large and small scale that are underway and either nearing technology transfer stage or seeking industrial partners to continue application development.

• Multiple-arm coordination: intuitively maneuvering large, ungainly workpieces

Industrial robots conduct most handling operations using single robot arms. In contrast, humans naturally use two hands to deal with the uncertainty in the center of mass location, to provide better orientation control, and to distribute the payload. Manipulation of objects using two or more robots should thus be conceptually intuitive to a human operator. Further, a human concentrates on how the object moves, rather than how to move arms to make the object move. One method of moving large and potentially unwieldy objects using multiple robotic manipulators in such an operator-intuitive manner has been recently demonstrated at SNL.

The ability to rapidly command multi-robot behavior is crucial for the acceptance and effective utilization of multiple robot control. To achieve this, a modular multiple-robot control solution is being pursued using the Sequential Modular Architecture for Robotics and Teleoperation (SMART) modular control architecture[1]. SMART allows the operator to describe robot behavioral modes in terms of graphical

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icons. Each icon represents a subnetwork in the complete robot system network. The user combines icons representing input devices, sensors, kinematics, simulated dynamics, constraints, and actual robot hardware to create a stable working system[2]. Using a graphical SMART editor, the user assembles the desired system. The editor automatically checks for completeness and viability, and then generates source code and starts scripts for execution. Currently, over 150 different SMART modules have been developed, ranging from trajectory (PATH) generation, to mapping robot kinematics from the world to joint frames (KIN), to filtering and terminating a network, to controlling robot motion in joint space.

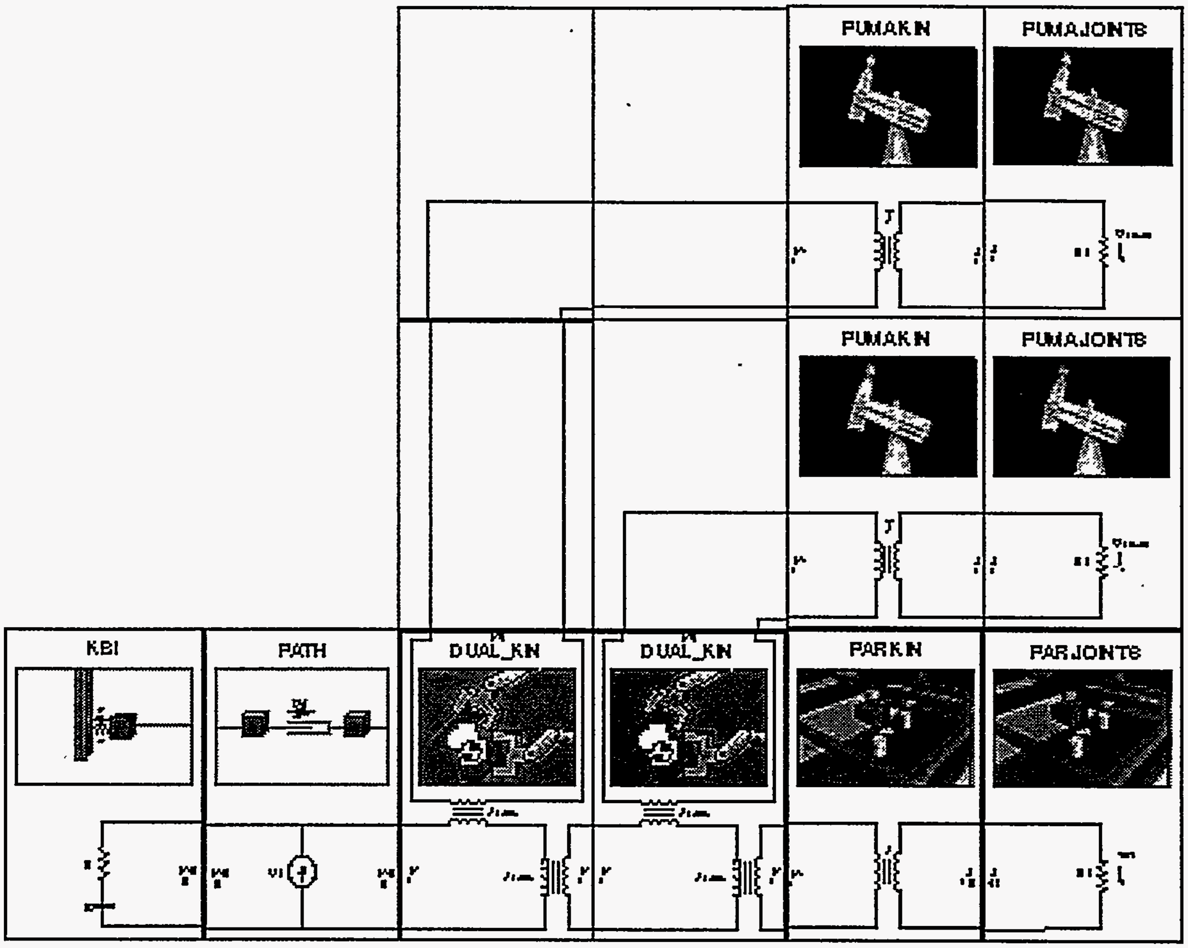


Figure 0-1 Multiple DUAL_KIN modules are used to create a three-robot behavior

A new module, DUAL_KIN, has been developed to allow multiple robots, previously controlled as separate stand-alone systems, to be controlled as a coordinated multi-robot system[3]. The DUAL_KIN module maps velocity and force information from a center point of interest on a grasped object to the tool centers of each grasping robot. Three-port network equations are used and mapped into the scattering operator domain in a computationally efficient form. Figure 0-1 shows a multi-arm SMART system using a DUAL_KIN module and a force-sensing module.

At the 1995 DOE robotics forum, the DUAL_KIN module was demonstrated in the multi-arm laboratory using two PUMA 760 and one overhead PaR 6-degree-of-freedom gantry robots. Eleven different behavioral modes were used to conduct the demonstration. Included in these were three different shared modes of operation involving each pair-wise combination of robots and one mode showing the combined behavior of all three robots. Figure 0-2 shows an operator concentrating on moving a large frame with a 6-degree-of-freedom input device, while robot motions are generated automatically, transparent to the operator.

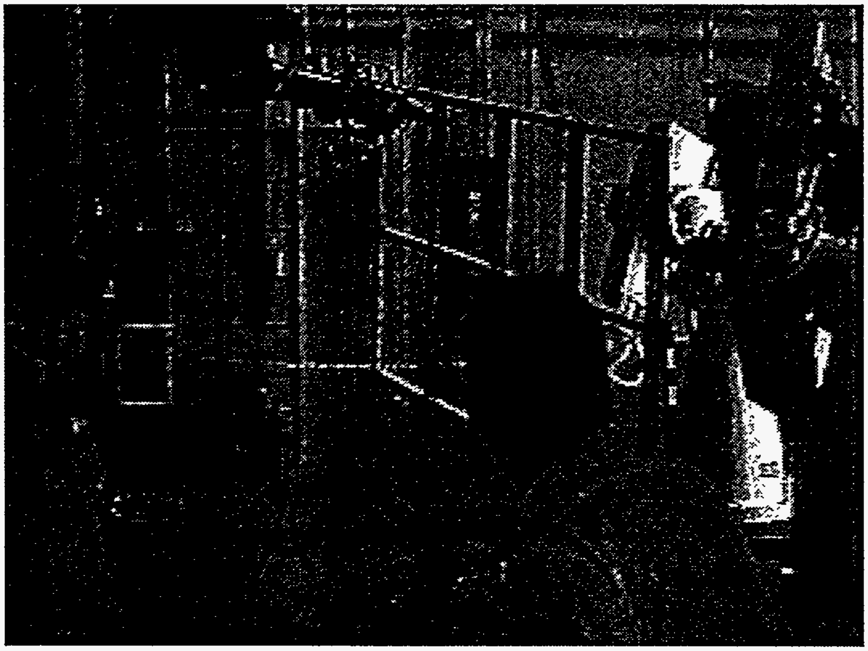


Figure 0-2 An Operator manipulates a large frame using a 6-degree-of-freedom space-ball. Movements of two cooperating robots are automatically generated.

The system was shown to move seamlessly between these different modes of operation in order to conduct both teleoperated and autonomous operations. The bilateral transmission of force information was shown to prevent overdriving the grasped object past robot singularities and joint limits. No stability problems occurred in any behavioral mode. The robots are currently being applied to large-scale decommissioning projects, in which the gantry robots conduct large part removal.

- **Simulation, analysis and graphical training capability for CP-5 research reactor dismantlement.**

Chicago Pile Number 5 (CP-5) research nuclear reactor at Argonne National Laboratory (ANL) is currently being dismantled. The DOE is taking the opportunity to develop and test remote and robotic dismantlement procedures, and Oak Ridge National Laboratory (ORNL) is coordinating DOE's Robotic Technology Development Program efforts at ORNL, Idaho National Engineering Laboratory (INEL), and SNL in support of ANL and the CP-5 dismantlement program. SNL is supporting the robotic application through building and maintaining the simulation model for all participants; providing the simulator capability to analyze various dismantlement options for feasibility, operator training, and costs and benefits; and developing task-based robotic programming to speed operations in the future.

Model

To facilitate communication among the participants, as well as serve as a basis for planning, simulation and analysis, a detailed graphical model of CP-5 was built (Figure 0-3) using TELEGRIP, a robotic simulation package by Deneb Robotics. The model includes the reactor vessel, piping and support structures, shielding, neutron beam ports and experiment insertion hardware, as well as the surrounding "containment" and support buildings. It is as accurate as possible, utilizing dimensions extracted from construction drawings, photographs and measurements.

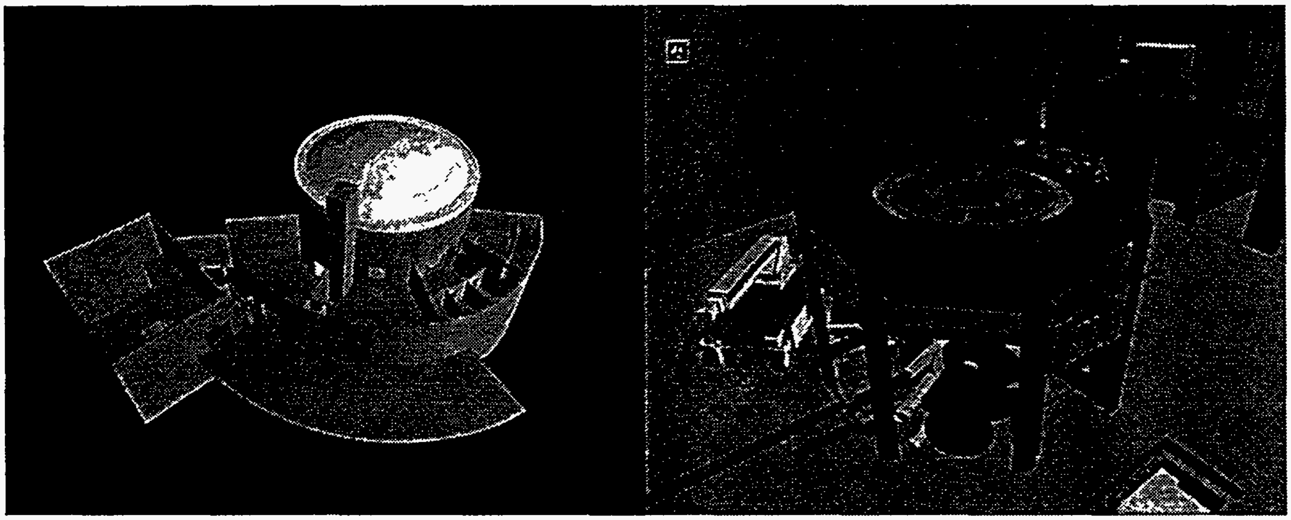


Figure 0-3: Computer model of Chicago Pile Number 5. Left: Building floor plan. Right: Reactor assembly with biological shield material invisible for clarity.

The model is maintained on a public server for access by the inter-laboratory team. It was augmented by INEL, adding the Dual Arm Work Platform (DAWP), and by ORNL working with Deneb Robotics to model the Schilling Titan III manipulators installed on the DAWP.

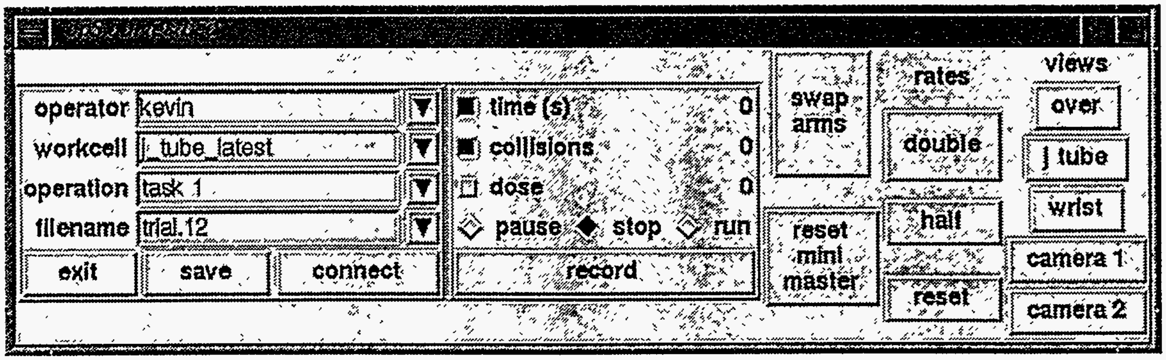
Operations analysis

There are many operations in the dismantlement of CP-5 requiring remote execution to maintain low worker exposure. For many of the operations there are alternative processes from which to choose. To help determine which alternative is best, feasibility and cost benefit analyses are desirable, based on realistic assumptions. The dimensional, kinematic and temporal assumptions for these analyses are supported by the simulation environment.

To produce the CP-5 simulation environment, SNL augmented the graphical model and basic simulation power of TELEGRIP to allow for a manual input device and appropriate simulator responses. The Schilling Mini-master, selected by ORNL to control the DAWP manipulators, was modified to connect to the SiliconGraphics workstation serial port (Figure 0-4). Drivers were written to translate Mini-master movements into control commands for the simulated Titan III robots. Since TELEGRIP normally requires internal programming to determine when a simulated object is grasped by a robot, control software was written to interpret when gripping is intended by the operator, and automatically generate the simulator command to "attach" the object to the gripper.

Figure 0-4 A Schilling Mini-Master manipulator control device drives the Dual Arm Work Platform manipulators in the CP-5 dismantlement simulation.

Automated tracking and graphical user interfaces were developed to track operator performance data and physical parameters during simulated operations. The current GUI is illustrated in Figure 0-5. Data includes tasks, operators, and quantitative information such as time to completion, number of collisions and radiation dose to critical machine components, for use in operator screening, training, and cost-benefit analysis.



operator: kevin
workcell: j_tube_latest
operation: task 1
filename: trial.12

■ time (s) 0
■ collisions 0
☐ dose 0

◇ pause ◆ stop ◇ run

Figure 0-5 Graphical user interface for tracking operator performance data in the simulated CP-5 tasks

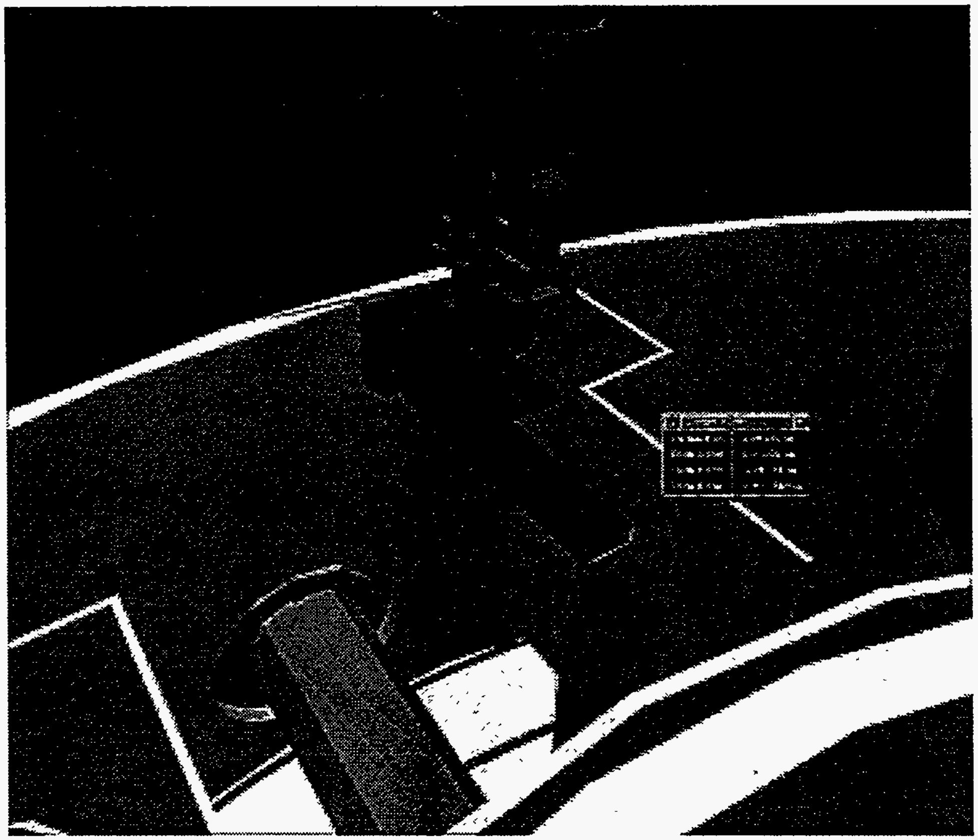


Figure 0-6 J-tube pipe and flanges to be removed from the CP-5 lower annular shield.

The simulation environment has been applied to one task to date. The removal of a pipe segment of the overflow system that passes through the lower annular shield, known as the J-tube, is expected to be one of the first difficult tasks to perform remotely. Flange bolts must be removed from both ends of the pipe segment before the annulus can be lifted out of the reactor. The difficulty is that the pipe is surrounded by a box structure within the annulus, open only at the top, hampering deployment of the manipulator and tooling. The J-tube configuration is shown in simulation in Figure 0-6.

A test run to determine if the robot can reach under the pipe to reach lower flange bolts revealed several problems with the intended procedure. First, the two available torque wrenches could not physically fit under the pipe sufficiently to reach the lower bolts. More importantly, the robot manipulator itself could not be configured to deploy the wrenches to the lower bolts without collision with either annulus or the pipe. This resulted in a recommendation to seek alternative procedures, such as cutting the pipe segment from the flanges prior to removing the bolts.

The average time for the operator to grasp and deploy the tooling near the J-tube (prior to attempting bolt contact) was 125 seconds, with an average of 7 collisions per trial. Radiation doses were not tracked. Trend analysis shows a clear decrease in both execution time and collisions, achieving a minimum time of 54 seconds and one single collision. This information was then added to a task flow model developed at ORNL for system performance evaluation.

ANL has indicated an interest in operator screening and training utilizing the simulation environment described here. By using the actual input device and accurate simulation models, operators can be introduced to the control and response of the manipulators without possibility of damage. Their performance on given tasks can be evaluated quantitatively, and improvements measured.

Other benefits include improved communications between program participants, sponsors and the public. The simulator has recently been demonstrated for ABB-Atom via video link. Multi-point viewing and operating capability has recently been integrated into TELEGRIP, enabling simultaneous viewing and shared control of the simulation. This will facilitate travel-free, real-time technical support from worldwide experts in the event that planning and execution difficulties arise.

Work is ongoing to improve the simulator environment. Response time of the simulated robot to the MiniMaster movement is being investigated for accuracy. Gripping currently takes place in simulation in any orientation of the gripper to the gripped object. We are currently investigating the gripping orientation of lowest energy for the gripper to come to rest, and will drive the simulation to that orientation to complete the operation. Though the simulation warns of collision, it currently allows penetration of solid objects with other objects. This will be prevented. Finally, automatic cutting and joining operations will be integrated into the simulation capabilities.

- **Miniature robots with volumes of 16 cm^3 and less are being developed for inspection and sensor deployment.**

Microrobotic systems have many potential applications both on land and in space. Researchers have for years suggested the possibility of minute robotic systems at the cellular level that would travel throughout the blood stream and repair clogged arteries. Miniature mobile robots, acting collectively, could possibly inspect or perhaps repair piping systems with small diameters or small access ports. Unattended mobile sensing platforms can assist in the verification of chemical, biological and nuclear treaty compliance verification by sensing controlled activities and moving for better sensor coverage. The military envisions miniature robotic systems which can be used to assist soldiers in the field for surveillance and inspection; searching, following and tagging; and locating and identifying targets. Microrobotic systems have also been envisioned as the next lunar rovers, extremely small and inexpensive to launch into space.

<u>MARV</u>

SNL has recently developed a 16 cm^3 (1 in^3) autonomous robotic vehicle which is capable of tracking a single conducting wire carrying a 96kHz signal. This vehicle was developed to assess the limiting factors in using commercial technology to build miniature autonomous vehicles. As a first step in development of micro mobile platforms, a simple vehicle was designed and built from the smallest commercial off-the-shelf components available. The result of the approximately 30 day effort was the Miniature Autonomous Robotic Vehicle, or MARV (Figure 0-7).

The development of MARV was conceived as a demonstration project in which commercially available components were integrated onto an in-house custom designed chassis to form an autonomous mobile vehicle. MARV consists of a 23.4 x 15.9 x 24.1 mm lexan frame which holds two Micro Mo 0816-008S DC motors, two 3 volt lithium cells, a Microchip PIC16LC71-04/SO microcontroller, two 4.4 x 8.9 mm printed circuit antennas, and electronics for conditioning the antennae signal and driving the motors. The vehicle has four wheels. Each rear wheel has a separate drive motor and a 15:1 worm reducer. The two antennas on the bottom of the vehicle are used to detect whether the vehicle's centerline is to the right or left of the wire containing the tracking signal.

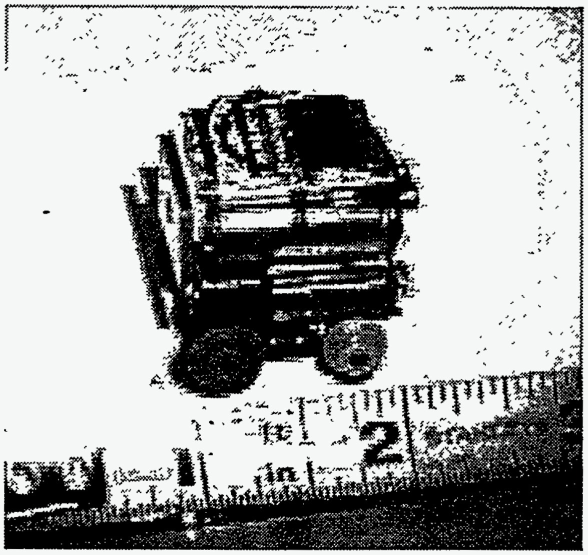


Figure 0-7 Miniature Autonomous Robotic Vehicle (MARV)

In the approximately 300 lines of assembly control code, a set of if/then statements in the embedded software jump between four finite states: SEARCH, ROTATE, TRACK, and BACKUP. MARV searches for the signal wire with a forward motion, rotates to acquire the wire, and tracks the wire. If the signal is lost, it will back up, searching for the signal until a time-out sends it into the search state. MARV can operate for approximately 20-30 minutes on a single set of batteries.

Current efforts

Efforts are now underway to reduce the size of machines and sensors. Automated microassembly techniques for machines with LIGA components of 100 µm diameters and 1µm tolerances are being developed. Micro-Electromechanical Systems (MEMS) have been developed and demonstrated at SNL ranging from sensors to gear trains to motors. These techniques are now being aimed at building a chemistry laboratory on a chip, which can be delivered to an area of interest on miniature robotic platforms.

To examine the possibilities of multiple miniature systems cooperating to accomplish tasks difficult for individual systems, SNL is working to understand collective behavior and its design. We have completed the framework of a scenario analysis and design software tool, which will be used to develop, analyze and program behaviors of miniature devices working together to perform tasks otherwise impossible for a single entity.

- **Biomedical sensors enhance automated prosthetic device production and fill laparoscopic surgery information gap.**

Sensors used for robotic applications are being adapted by SNL for use in the field of medicine. Three recently-developed devices are described in this section. These are 3-dimensional ultrasound imaging for prosthesis fabrication and diagnostic imaging, a photo-endoscopic sensor for blood vessel detection, and the addition of a force-torque sensor to standard laparoscopic surgery tools.

<u>Ultrasound imaging for prosthetic device production</u>
Approximately 60,000 lower extremity amputations are performed each year in the United States for a variety of medical reasons[4]. Ninety-seven percent of these patients are candidates for prosthetic devices to provide near-normal function of the residual limb. The most important part of the prosthesis is the socket, which interfaces the leg and the mechanical extension, since the design and fit of the socket determines patient acceptance, comfort, suspension and energy expenditure.

The average amputee will need three to five new prostheses within the first five years after amputation because of changes in the residual limb, resulting in failure of the socket and repetition of the fitting and manufacturing process. To speed this process and reduce the cost, changing from hand-casting to an automated operation has long been a goal. Since CAD models can be used to automatically program machine tools to create the sockets, measurement of the residual limb and conversion of the data to CAD format is the challenge. Various methods including light, computer assisted tomography (CT), magnetic resonance imaging (MRI) and linear potentiometers have been used to collect limb measurements. Variations on lighting and external measurement devices do not provide data on bone structure needed for support design. CT and MRI are both expensive and slow, and CT uses ionizing radiation, which could be harmful to the patient.

SNL, working with the University of Texas Health Sciences Center at San Antonio (UTHSCSA), has developed a proof-of-concept ultrasound imaging device to obtain surface skin and bone geometry data for relatively low-cost automated socket fabrication. The system consists of an SNL-developed mechanical scanner, ATL ultrasound machine, analytical software and CAD software developed at UTHSCSA (Figure 0-8).

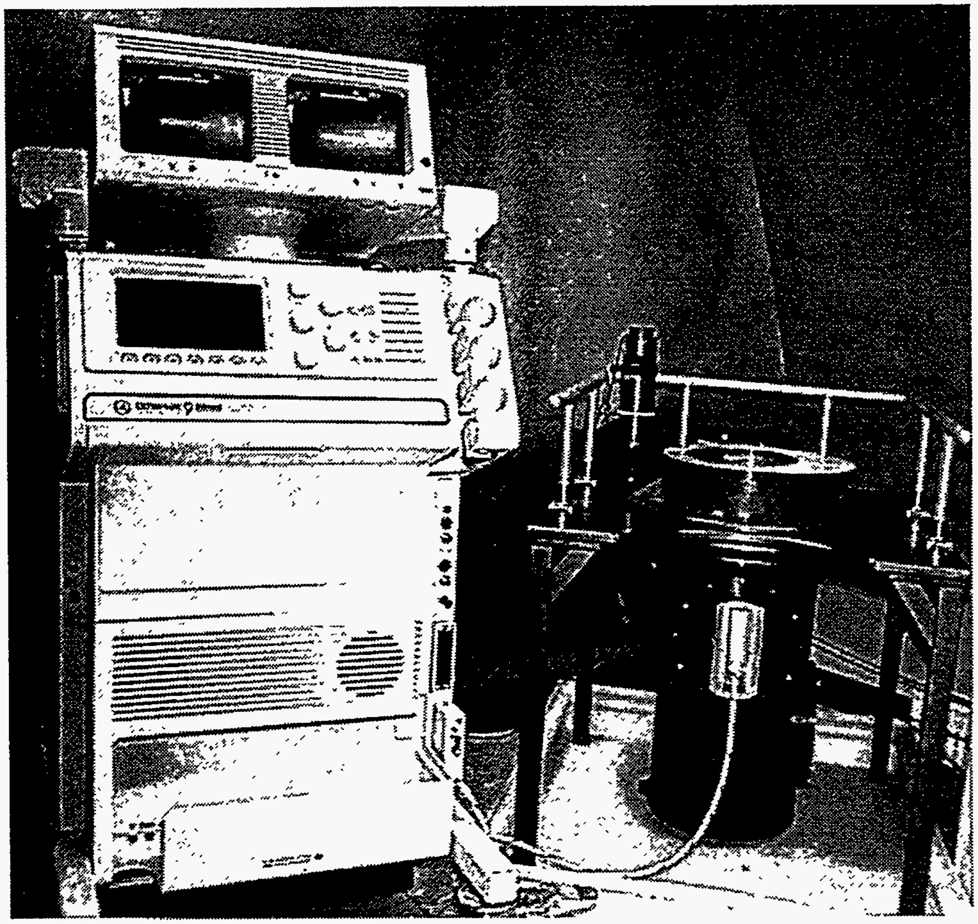


Figure 0-8 Mechanical Scanner with ATL Ultrasound Machine

To create a 3-dimensional image from a planar imaging device, SNL developed a mechanical scanner. The transducer is mounted on a scanning tank window and rotates with the tank about the leg. The volume swept by the transducer is then reconstructed by software using angular rotations and polar interpolation. Registration algorithms were developed for volumetric comparison of the ultrasonic images to the CT images. Volumetric comparisons were determined best due to differences in leg positions for each of the measurement techniques. Figure 0-9 illustrates the registered volumes using ultrasound and CT data.

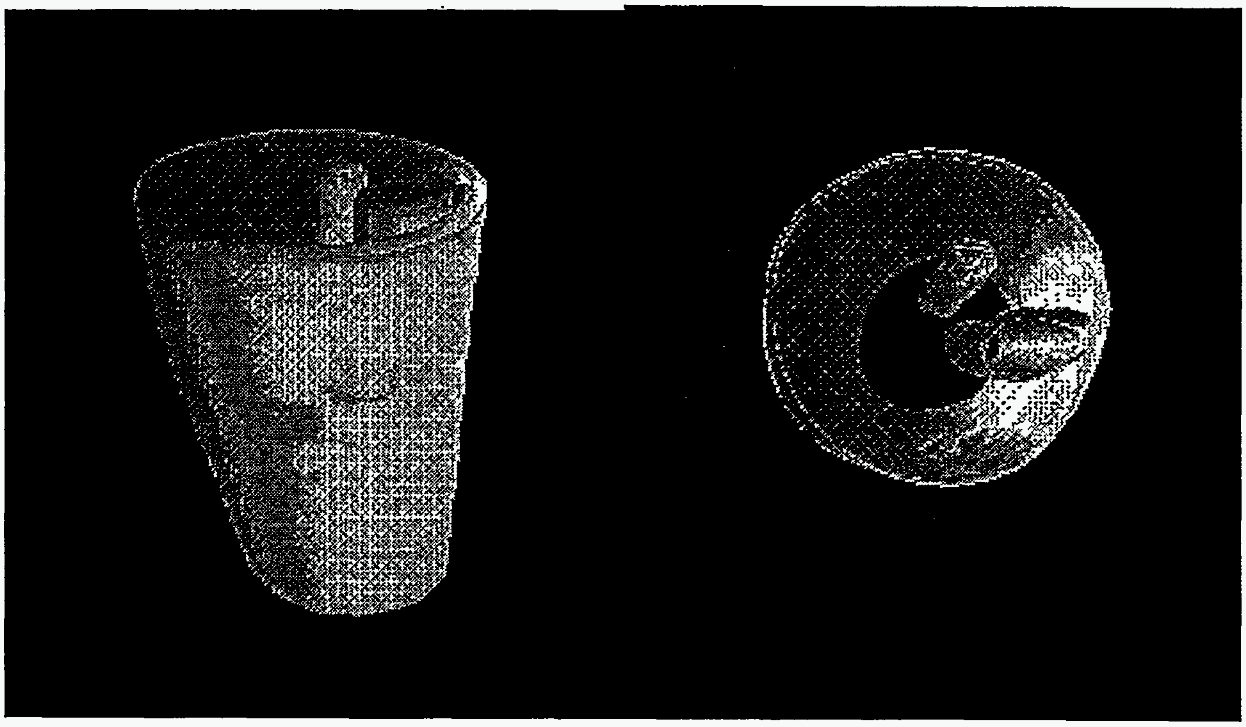


Figure 0-9 Registered ultrasound and CT volumes: Left - side view, right - top view

Clinical trials using 9 volunteer subjects were conducted at UTHSCSA to compare the ultrasound and CT volumetric images. Among these patients, values fell primarily within the target range of 3 percent. Sources of error included the patients' ability to support his/her own weight, the amount of uncontrollable tremor in the patient, and the flexibility of the patient.

This data was then fed into the UTHSCSA-developed CAD package called SOCKETS. SOCKETS allows the prosthetic practitioner to interactively modify the graphical prosthetic socket to better bear weight and reduce pressure in the areas around the bones.

Work is continuing in the area of high-resolution ultrasonic imaging. Current sponsors have interests in patient assessment on the battlefield and in interoperative monitoring.

Minimally invasive tools

Minimally Invasive (MI) tools and procedures are being used to reduce trauma to patients when compared with open surgery and to reduce recovery time and hospital stay. Minimally invasive procedures are limited for two reasons:

- the necessity to use characteristically long and slender tools operated at distances of up to several feet from the tool tip. These tools are inserted into the body cavity through an orifice, or small incision.
- they remove the surgeon, or physician, from the patient, limiting and distorting the sense of touch, tissue characterization, and visual acuity.

SNL has addressed the need for additional information by developing two devices. The Force and Torque Sensor (FTS) is used to transmit force and torque interaction information to the surgeon in real time. The Photo-Endoscopic Sensor (PES) was developed to detect blood vessels in the area where the surgeon might be excising tissue, etc.

Force and Torque Sensor

The FTS incorporates a customized 6 axis force/torque sensor built into a standard laparoscopic tool. Figure 0-10 shows the prototype device. As the surgeon performs an operation, forces detected at the sensor are displayed visually using a bar-chart next to the video display from an inserted camera. The display has been calibrated for tissue damage risk while grasping and pulling.

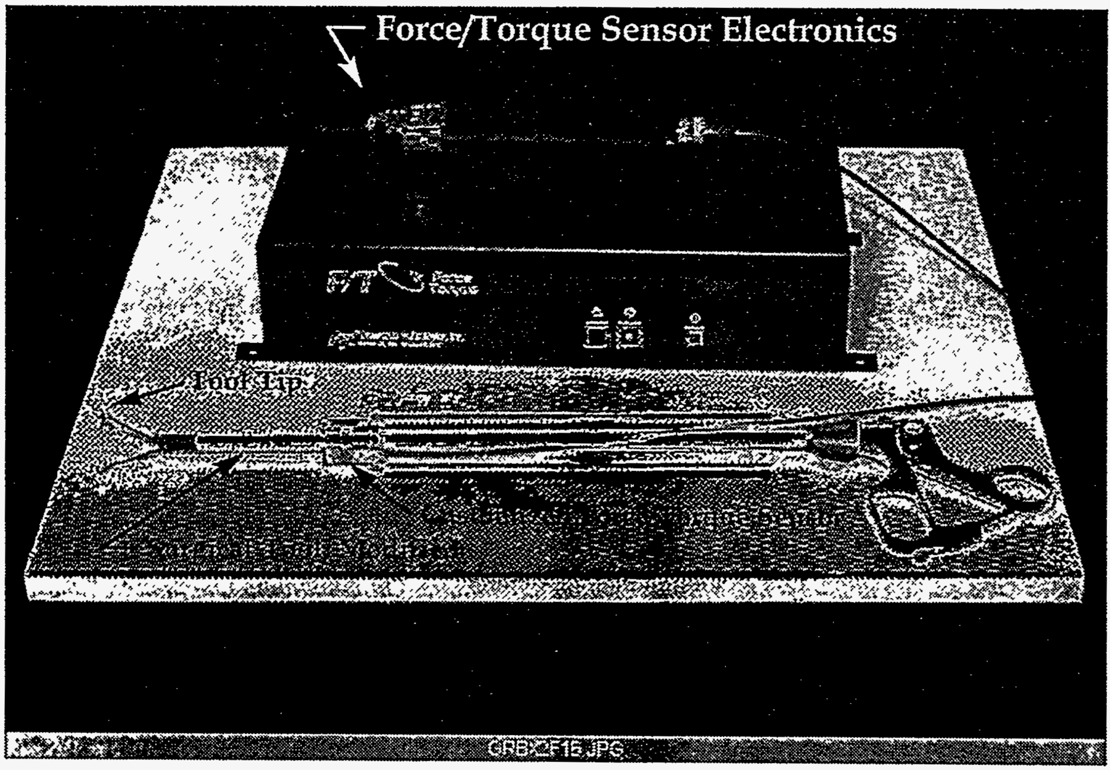


Figure 0-10. Prototype Force/Torque Sensor (FTS)

Photo-Endoscopic Sensor

The ability to detect sub-surface blood vessels will reduce the likelihood of damaging blood vessels; damaging blood vessels is a leading cause of surgeons having to convert from a laparoscopic to an open procedure. The Photo-Endoscopic Sensor (PES), shown in Figure 0-11, is designed to detect blood vessels larger than 1 mm in diameter beneath the surface of tissues. The PES sensor functions by emitting and gathering light using three glass fibers with polished ends. The two transmitting fibers in the sensor shine a light at a tissue surface. A portion of that light reaches a blood vessel, is reflected back to the probe, and is carried to the receiver. Variations in the amount of reflected light at different wavelengths are used to locate subsurface structures.

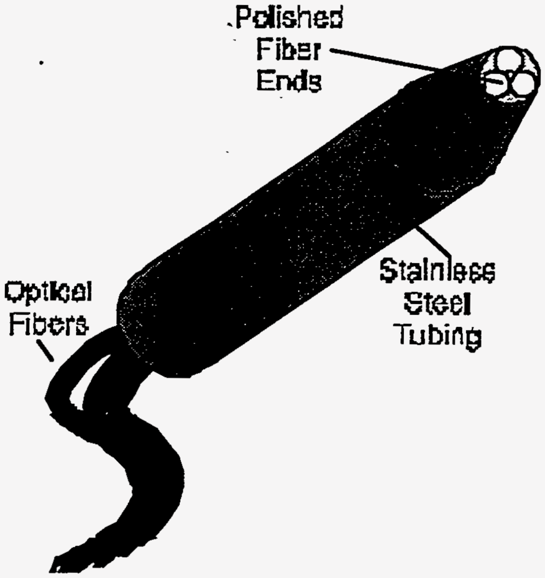


Figure 0-11 Photo-Endoscopic Sensor (PES)

- **A teleoperated microsurgical device has been developed to enhance surgeons' dexterity.**

MicroDexterity Systems, Inc. (MDS) and SNL are collaborating on the design of a six degree-of-freedom (DOF) surgeon-controlled micropositioner (SCMP) and a six DOF surgeon-controlled master (SCM) for use in microsurgery[5]. The system must be backdriveable, light, fast, small, frictionless, backlash free, and capable of sufficient force and frequency response for smooth kinesthetic feedback or haptic sensations. Conventional robotic technology is inadequate for microsurgical applications due to the fact that their main purpose and mechanism design methodology is to do repetitive tasks. The ideal force reflecting teleoperation system would provide a completely transparent interface between the user and a robot. For example, when there is no contact between the SCMP and the environment no forces should be applied to the SCM. Likewise, if there is contact, the surgeon should only feel the scaled forces at the tool tip of the SCMP.

The robotic system designed and under test at SNL (Figure 0-12) has attempted to address many issues ranging from reducing mass and friction, while maintaining rigidity and backdriveability. Linear motors along with some unique mechanism designs attempt to transfer five linear motions to three linear motions (X,Y,Z) at the tool-tip along with 2 angular motions (roll, pitch). The linear motors are not directly mounted on the mechanism. This reduces the overall mass of the device significantly. The final angular motion is accomplished by attaching an extremely small rotary motor at the tool tip. The backdriveability of this motion is of much less importance in the overall scope of microsurgery.

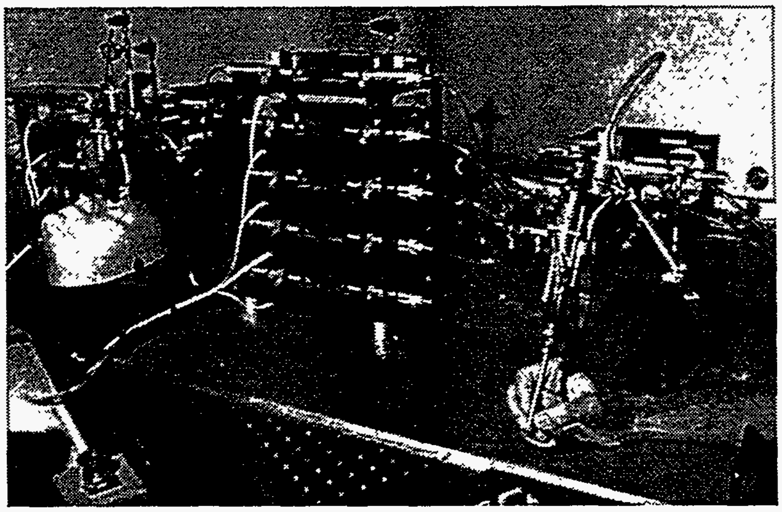


Figure 0-12 Microsurgical robot prototype system

The technologies that are currently being developed by this project are expected to enhance the skills of surgeons, improve the success rates for existing microsurgical procedures, make new high-dexterity procedures possible, and ultimately reduce surgical costs by increasing the precision and speed of operations.

Acknowledgments

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