

**TeleOperator/telePresence System (TOPS)
Concept Verification Model (CVM)
Development**

Mike S. Shimamoto
NAVAL COMMAND, CONTROL AND OCEAN SURVEILLANCE CENTER
RDT&E Division (NRaD) Hawaii Detachment
PO Box 997
Kailua, Hawaii, 96734 U.S.A.

ABSTRACT

The development of an anthropomorphic, undersea manipulator system, the TeleOperator/telePresence System (TOPS) Concept Verification Model (CVM) is described. The TOPS system design philosophy resulting from NRaD's experience in undersea vehicles and manipulator systems development and operations is presented. The TOPS design approach, task teams, manipulator and vision system development and results, conclusions, and recommendations are presented.

INTRODUCTION

A major step has been taken toward the development of an advanced, telerobotic, undersea work system with the TeleOperator/telePresence System (TOPS) Concept Verification Model (CVM) (Figure 1). The long term objective of the TOPS program is to develop the technologies required to build remote work systems that are functionally equivalent to a diver in performing unstructured undersea tasks. Such a remotely controlled manipulator system would not be constrained by the diver's operational limitations in hazardous areas, great ocean depths, cold temperatures, and submerged operating time. The emphasis of the project is on developing the capability for performing tasks that require the dextrous, adaptive, and judgmental capabilities of man rather than on performing precise, well-defined tasks that can be addressed by purely robotic systems or specialized tools.

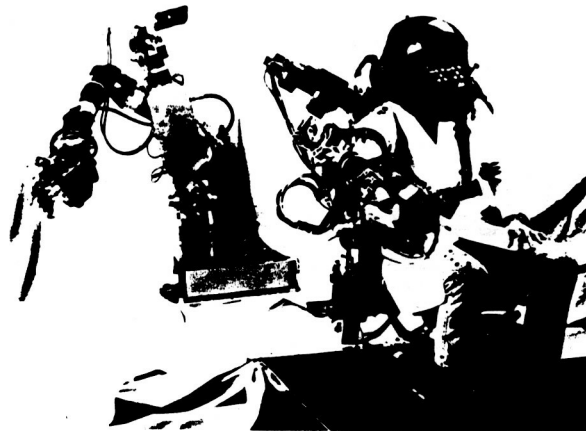


Figure 1. TOPS CVM

BACKGROUND

Organizations contributing to the development of the TOPS CVM and their areas of expertise are as follows: NRaD (US Navy remotely operated vehicle and manipulator development); Sarcos, Inc. (SI) and the Center for Engineering Design (CED) at the University of Utah (dextrous hand/arm, entertainment robots, and robotic component development); and Armstrong Aerospace Medical Research Laboratory (AAMRL) at Wright-Patterson Air Force Base and Technology Innovations Group (TIG) (helmet mounted display vision systems development).

Teleoperator Systems Development at NRaD

Over a span of two and a half decades, the Advanced Systems Division of NRaD's Hawaii

Detachment has developed manned undersea vehicles; unmanned, remotely operated undersea vehicles (ROVs); unmanned remotely operated ground vehicles (UGVs); and teleoperated manipulator systems^{1,2,3}.

During the development of the Remote Unmanned Work System (RUWS) (Figure 2) and several other ROVs, test operations were conducted in recovery, inspection, and emplacement tasks (Figure 3). The "lessons learned" from those operations provided impetus to the TOPS program.

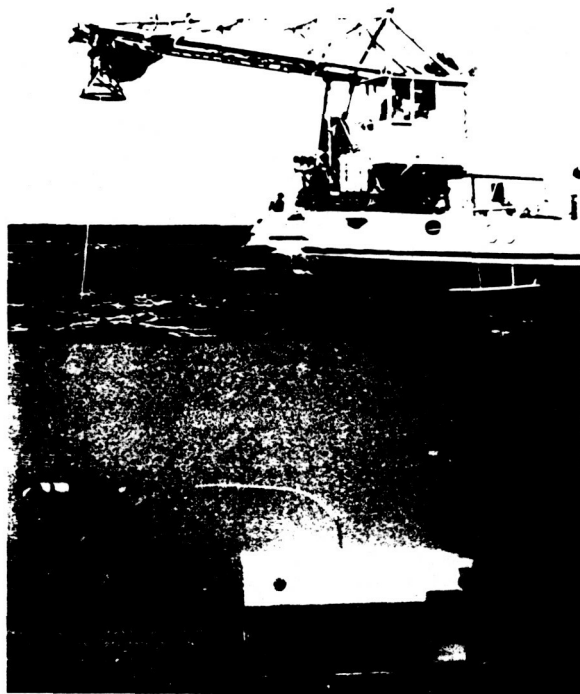


Figure 2. RUWS.

Although a set of hydraulic tools had been designed and fabricated for use by the RUWS manipulator, additional special tools were often required for new tasks (Figure 4). During several operations, the tools had to be modified or new tools fabricated, because the task was not quite as it was "supposed to be." Although, lots of pre-operations planning were done and special configurations for the vehicle were implemented, few missions were completed without difficulty. Navy salvage operations, by nature, usually have many "unstructured" tasks when recovering wreckage and items from wreckage.



Figure 3. Manipulator work.



Figure 4. Vehicle configuration.

Simple diver tasks, such as putting a snap hook onto a shackle, proved to be difficult because of the limitations in dexterity of the manipulator and mobility of the vehicle. If currents were present, the object to be worked on was approached with the vehicle heading into the current; this frequently resulted in an orientation to the task that was less than ideal for the manipulator. Maneuvering the vehicle for proper positioning usually resulted in agitation of the bottom sediment, which obscured the remote operator's visibility. Conditions such as

those for each mission seemed to provide unique challenges to the operators even when the missions consisted of fairly simple tasks. The operators were often more frustrated than fatigued in attempting to complete the tasks for a successful mission. Tasks that could easily be performed by divers were not at all trivial for an ROV work system. These lessons indicated that a diver-equivalent work system might provide the work capability needed for many undersea missions where present ROV and manipulator systems are inadequate. The capabilities of such a system could also be applied to other hazardous missions on land and in space.

Diver Tasks

An assessment of tasks performed by Navy and civilian divers determined: (1) the importance of various tasks within dive missions, (2) the manipulative and sensing capabilities used by the divers to perform the missions, and (3) the key design parameters for the development of a diver-equivalent manipulator system.

In determining the importance of various tasks within dive missions, it became clear that the major differences between what divers could do and what could be done with manipulators were that divers could perform a series of complex tasks and adapt to the differing tasks to successfully complete a mission. The divers used their own manipulative and sensing capabilities that were required to complete the tasks. Maneuverability, dexterity, and full sensory capability were key to the adaptability and versatility required to successfully complete the variety of tasks within the missions.

In determining the key design parameters for a diver-equivalent manipulator system, it became evident that the best configuration that would allow an operator to perform like a diver was a system configured the same way as the human operator (i.e., an anthropomorphic configuration). A manipulator system with joints and links that matches the operator's (kinematic equivalent) and with all manipulative appendages and sensory systems in the same relative positioning (spatial correspondence) as the operator's appendages and sensory systems would allow the operator to perform the tasks as if he/she were present at the work site.

A system that maintains spatial correspondence between the slave and the operator allows the operator to use his/her experiences from infancy to the present. If spatial correspondence is lost, people can adjust, but only by sacrificing performance. The loss in performance shows up in objective measures such as additional training required to attain proficiency, higher error rates, longer times to complete the tasks, as well as increased mental and muscular fatigue by the operators⁴.

Anthropomorphic Manipulator Development

The first anthropomorphic (human configured) manipulator developed at NRaD was the Remote Presence Demonstration System^{1,2} (nicknamed "Greenman"), shown in Figure 5. It was assembled in 1983 using MB Associates arms and an NRaD-developed torso and head. It had an exoskeletal master controller with kinematic equivalency and spatial correspondence in the torso, arms, and head. Its vision system consisted of two 525-line video cameras each having a 35° field of view and video camera eyepiece monitors mounted in an aviator's helmet.



Figure 5. Remote Presence Demonstration System.

Greenman provided NRaD with valuable experience in teleoperation and telepresence issues and designs. Even with its simple claw hands and no force or tactile feedback, novice operators could readily perform manipulative tasks without training. However, it clearly showed that dextrous hands, force feedback, and a high-resolution vision system were necessary for diver-equivalent work capability. Also, the Greenman was not designed for in-water use, and

demonstrations of in-water work was deemed necessary to fully demonstrate the diver-equivalent concept.

TOPS PROGRAM DEVELOPMENT

TOPS Long-Term Concept

The long-term concept for a diver-equivalent manipulator system is shown in Figure 6. The master controller "fits" the operator like a business suit and senses his/her hand, body, and head motions. The slave manipulator mimics the operator's motions, senses its interaction with the environment, and provides sensory feedback to the operator via the master controller in a manner natural to him/her.

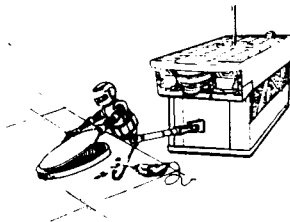
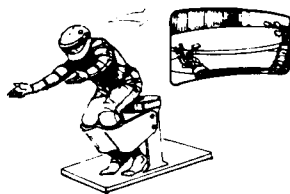


Figure 6. TOPS Concept.

An assessment was conducted of available, near-term, and long-term technologies in planning for the development of the first TOPS model to verify the concept. Because the first model would be a 3-year project only, long-term technologies were not included in the project scope.

Long-term technologies identified for future TOPS systems were: (1) tactile telepresence systems, (2) high-definition TV (HDTV), (3) human equivalent dextrous hands, (4) the integration of virtual reality with the vision system, (5) advanced manipulator controllers, and (6) passive sonar for underwater directional hearing .

TOPS CVM

The first model of TOPS was called the Concept Verification Model (CVM). This model incorporated available and near-term teleoperation and telepresence technologies including (1) dextrous hands, (2) high-fidelity force feedback, (3) high-resolution head-coupled vision, and (4) an integrated, natural master controller with spatial correspondence. The major thrust of the technologies was in the development of the two major subsystems: (1) the manipulator and (2) the vision system.

TOPS CVM Manipulator Development

The development of the TOPS CVM manipulator was contracted to Sarcos, Inc. and the Center for Engineering Design at the University of Utah. The hand was developed in the first phase; the arm was developed and then integrated to a revised hand in the second phase; and the torso and head were developed and integrated in the third phase. The supporting control system was developed throughout all phases.

In the first phase, the hand development consisted of finger, hand, and wrist design concepts; tendon, actuator, and valve evaluation and development; sensor and supporting structure development; and antagonistic (pull-pull) servo control system development. A brassboard, 9-degree-of-freedom (DOF) hand was developed incorporating a 4-DOF thumb, a 3-DOF index finger, and a 2-DOF middle finger (Figure 7). The hand was attached to a 3-DOF wrist incorporating coincidental axes. The exoskeletal hand master represented a major design breakthrough where the structure fit on the backside of the hand but had virtual joints that matched the operator's finger joints. The brassboard hand was demonstrated at the end of the first phase (1 year). Demonstrations showed that the hand had the capability to perform standard hand grasps and manipulate various objects (such as threading a #10 nut onto a stud, and grasping and using standard hand tools), and showed high-sensitivity force feedback with high inter-system stiffness.

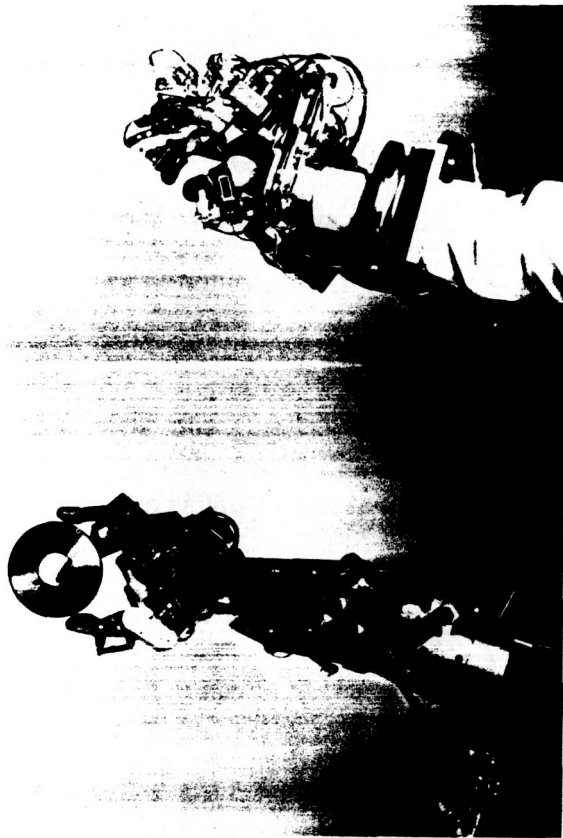


Figure 7. TOPS CVM brassboard hand.

In the second phase, the hand was revised while the arm was developed, then the arm and hand were integrated; low-friction rotary actuators were developed; and development of high-performance servo system components and controllers was continued. The arm was designed with a 3-DOF shoulder and 1-DOF elbow. The 3-DOF shoulder was designed to allow forearm/elbow orientations for various work task requirements. The exoskeletal arm master allowed full, natural operator control of the slave manipulator.

In the third phase, the torso and head were developed; subsystem and component development of valves, actuators, tendons, sensors, and hand designs were continued; all subsystems were integrated; then the system was tested in water. The 3-DOF torso was developed to provide a natural, short-range mobility and repositioning platform for the arm and vision. The 3-DOF head was developed to provide natural, spatially correspondent visual positioning

capability. Force feedback was not incorporated in the torso and head.

TOPS CVM Vision

The development of the vision system capitalized on the efforts by AAMRL on helmet mounted display (HMD) systems for the US Army's Light Helicopter, Experimental (LHX) program. After evaluating HMD prototypes for the LHX, a "pancake window" HMD configuration was selected for TOPS and a contract was awarded for an HMD to Technology Innovations Group (TIG) of New York. The HMD included a pair of 1023-line, monochrome CRTs with 68° field of view optics (approximately the view from a diver's mask); air cooling for comfort; and a "clamshell" rear-hinged section to make it easy to put the helmet on and take it off (Figure 8).

The remote portion of the vision system consisted of a pair of 1023-line monochrome cameras with fixed-focus lens mounted in an underwater housing.

A sophisticated display electronics package was acquired from AAMRL. The display electronics (developed for the LHX program) allows precise distortion correction for each channel, video signal, and CRT display. The correction parameters for each item can be stored on disk to allow rapid component changeout and reconfiguration.

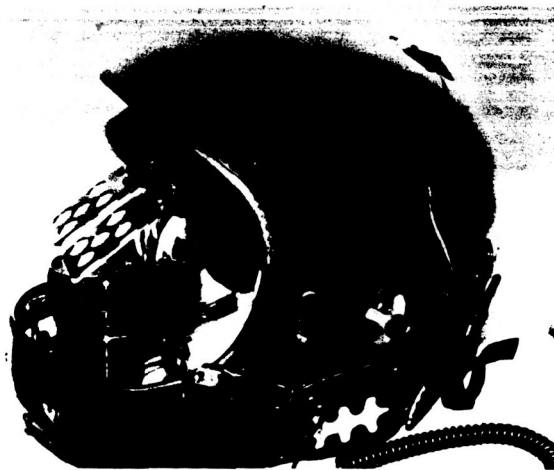


Figure 8. TOPS CVM Helmet Mounted Display.

TOPS CVM Overall Objectives Met

The overall TOPS CVM technical objectives were met in the development of an advanced manipulator system that begins to approach diver work capability. A high dexterity (22 DOF) manipulator with high-fidelity force feedback and a high-resolution, head coupled, stereo vision system was achieved. The combination of high dexterity that is kinematically equivalent to the operator, good force reflection, and a spatially correspondent 3-D vision system contributes to a high level of telepresence, i.e., the perception that the system is transparent to the operator. The operator feels that he/she is at the work site performing the task, and can concentrate on the task and not on operating the system.

Lessons Learned

Very valuable lessons were learned during the development and testing of the TOPS CVM⁵. The manipulator demonstrated great potential for performing a variety of manipulative tasks. The force reflecting exoskeletal system was natural and easy to use. However, subtle differences in kinematics and materials had major impacts on system performance. When link lengths and joint axes of the master controller did not properly match the operator's links and joints, and when grasping and positioning were not replicated exactly, the operator usually worked with significantly more caution and at a reduced speed. The fingertip configuration and materials of the slave hand also impacted the ability to securely grasp objects and, hence, the operator's confidence and speed of task performance. The compensation for gravity in the hand and arm for all areas of the workspace is very important to overall system performance and in the minimization of operator fatigue. Also, the capability to freeze operator selected joints would be very valuable for fine positioning tasks.

The tendon system proved too delicate, bulky, and complex for underwater operational systems. Tendon technologies that more closely replicate the human tendon system need to be developed.

The torso proved very useful in extending the manipulator's work volume and capability, in changing the viewing perspective, and in providing

a "natural zoom" capability (the ability to position the cameras closer to the work task simply by leaning toward the object).

CONCLUSIONS/RECOMMENDATIONS

Telerobotic systems will continue to be important for environments and tasks that are hostile to humans, but where man's cognitive and manipulative capabilities are needed. This case is particularly true for accidents where explosives, chemicals, nuclear materials, extreme heat or cold, etc., would expose humans to great danger. Accidents also present the high probability of occurrence of unstructured tasks that need to be performed to accomplish the mission.

Unstructured tasks usually require that full manipulative, sensory, and cognitive capabilities be employed. Any manipulative or sensory capability that a manipulator system does not provide is a "handicap" to the operator. The TOPS CVM represents a giant step taken towards minimizing the "handicaps" an operator inherits with a typical manipulator system.

However, as discussed in the section on Lessons Learned, continued refinements are needed in the TOPS CVM design to improved operator machine interfaces and produce a ruggedized, smaller hand for an operational system.

The next development phase requires continued developments in component technologies for increasing hand dexterity, providing underwater directional hearing capability, enhancing vision, and providing tactile telepresence.

Component development required for increased hand dexterity include reliable, low-stiction tendons, biological-like lubricants, and compact tendon routing technologies; small, responsive, lightweight, muscle-like actuators; finger- and palm-padding type material; and tough skin-type material.

The development of small, high-definition TV cameras and monitors are needed for 20/20 color vision systems.

REFERENCES

1. HIGHTOWER, J.D. and SMITH, D.C., "Teleoperator Technology Development," Proceedings of the 12th Meeting of the United States-Japan Cooperative Program in Natural Resources, San Francisco, CA, 1983.
2. HIGHTOWER, J.D., SMITH, D.C., and WIKER, S.F., "Development of Remote Presence Technology for Teleoperator Systems," 14th Meeting of the United States-Japan Natural Resources Committee, September 1986.
3. MURPHY, D.W., "Advances and Experience with Teleoperated Systems Incorporating Remote Presence," 17th Meeting of the United States-Japan Cooperative Program in Natural Resources, May 1991.
4. PEPPER, R.L., "Human Factors in Remote Vehicle Control," 1986 Annual Meeting of the Human Factors Society, 1986.
5. SMITH, D.C. and SHIMAMOTO, M.S., "TeleOperator/telePresence system (TOPS) Concept Verification Model (CVM) Testing and Demonstration, Final Report," unpublished, July 1991.