

# Man-Machine Cooperation in Advanced Teleoperation

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**Abstract** – Teleoperation experiments at JPL have shown that advanced features in a telerobotic system are a necessary condition for good results, but that they are not sufficient to assure consistent good performance by the operators. Two or three operators are normally used during training and experiments to maintain the desired performance. An alternative to this multi-operator control station is a man-machine interface embedding computer programs that can perform some of the operators functions.

In this paper we present our first experiments with these concepts, in which we focused on the areas of real time task monitoring and interactive path planning. In the first case, when performing a known task, the operator has an automatic aid for setting control parameters and camera views. In the second case, an interactive path planner will rank different path alternatives so that the operator will make the correct control decision. The monitoring function has been implemented with a neural network doing the real-time task segmentation. The interactive path planner has been implemented for redundant manipulators to specify arm configurations across the desired path and satisfy geometric, task and performance constraints.

## I INTRODUCTION

Advanced teleoperation systems are characterized by computerized features aimed at reducing the operator's effort and enhancing his concentration during tasks. Typical features are force reflecting control joysticks, mixing of video images with computer graphics and advanced control modes such as sensor or model-referenced control. These features achieve a level of transparency between operator and task that assures good awareness of the remote task status.

The teleoperation experiments carried out in the Advanced Teleoperation (ATOP) laboratory of the Jet Propulsion Laboratory (JPL) have shown that these features are necessary for good results, but not sufficient for consistent performance. The control of the many complex features of advanced teleoperators often results in excessive mental load and fatigue even during simple realistic experiments. To avoid this potential problem, two, often three, operators are used to manage the ATOP system during training and experiments. A primary operator is in charge of the manipulation and the others carry out support functions or serve as trainers. The multioperator approach is convenient when there are no constraints on the manpower available at the control station, but, when its volume is constrained, the man-machine interface should be controllable by a single person without compromising performance and task completion time. Thus the need for automatize some of these functions.

Most of the activities of the supporting operators are quite simple and yet very time consuming and could, in principle, be replaced by computer programs embedded in the man-machine interface. Some of these operations include setting the manipulator control gains, moving cameras and lights and operating the data acquisition functions. All the values in these functions are predetermined and the only free variable is the time at which those functions have to be done. Other features that should be performed under computer supervision because of their computational requirement, are task and path planning. A man-machine interface embedding these tools would cooperate with the primary operator by providing direct suggestions, presenting command alternatives and monitoring performance fluctuations.

To test the feasibility of automatic tools of this type, we have implemented two prototypes of an automatic

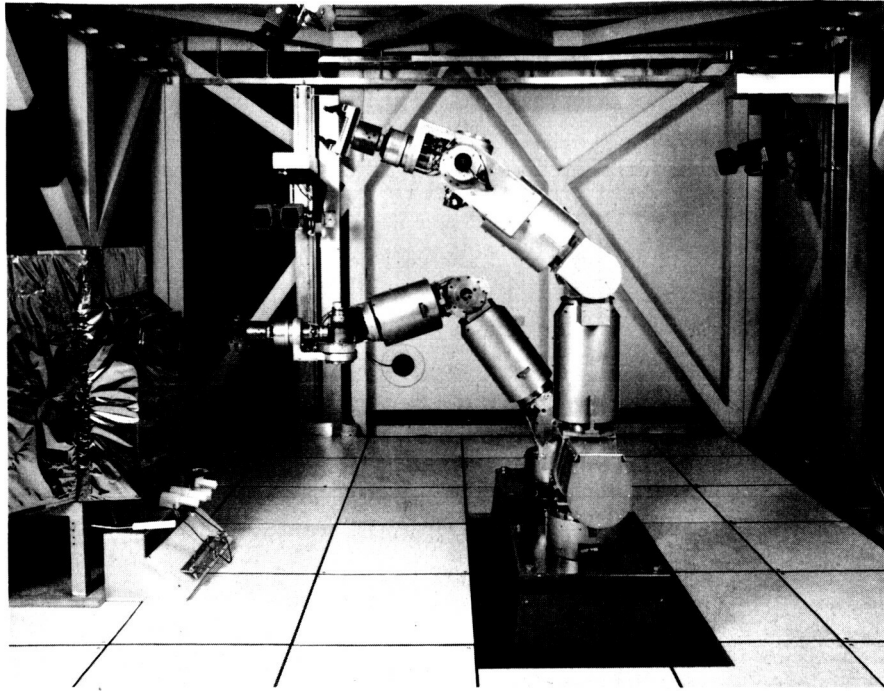


Figure 1: The JPL Dual Arm Advanced Teleoperator

monitoring program and of a redundant manipulator planner. The first tool is based on a neural-network for recognition of task phases and real time task measurement and it will permit the flexible automation of some task activities and the generation of feedback messages to the operator. In this way, a cooperative environment can be set, in which the telerobot and the operator share duties and monitoring functions of a teleoperated task. This approach would extend the paradigm of supervised control to the case in which the telerobot monitors and supervises the operator actions [4].

The second tool that we have also developed is an interactive path planner for redundant robots that allows the operator to specify arm configurations across the desired path satisfying geometric, task and performance constraints. Redundant manipulators are designed to enhance dexterity and robustness in task execution because they are equipped with more degrees of freedom (dof) than the minimum required by the task space. These manipulators allow the operator to carry out the primary manipulative task and, at the same time, to satisfy additional constraints such as avoidance of singularities and joint limits, maximization of manipulability indices, satisfaction of impedance characteristics, collision avoidance and fault tolerance. These constraints are satisfied

by using the redundant dof's of the manipulator, while maintaining the position and orientation required by the task. These motions of the manipulators are called self motions and the space in which they are executed is the manipulator null space.

When redundant manipulators are used in teleoperation, there are additional technical issues that relate to the operator's role in resolving the redundancy. Information must be provided to the operator to understand the effects of self motions in a meaningful and natural form.

Next section gives a brief description of the elements of the ATOP system and of its operator interface. Our initial results in developing a task model that can be used for interface/operator interaction are presented in section III. Section IV presents a brief summary of the control problems of redundant manipulators, of the specific issues of redundant teleoperation and of our parameterization approach [7]. The conclusion summarizes the paper and presents our current research and development directions.



Figure 2: The JPL ATOP Operator Interface

## II THE ADVANCED TELEOPERATION SYSTEM

The Advanced Teleoperation Laboratory (ATOP) is physically divided into two parts: the remote site and the local site. The main features of the remote site are:

1. A *Camera Positioning System* consisting of a steel frame capable of supporting five movable TV cameras. Currently, the frame supports three cameras mounted on pan/tilt platforms attached to computer controlled beams moving on the frame sides and ceiling. A monoscopic camera is mounted on the ceiling and one on a side beam, while a stereo camera is mounted on the other side beam.
2. A *Dual Arm System* consisting of two AAI 8 degree-of-freedom redundant manipulators, two Model C JPL Smart Hand and two sets of Universal Motor Controllers (UMC) systems (fig. 1). The UMC electronics performs the joint servo, the inverse and direct kinematics of the redundant manipulators, and handles the communication with the smart hands and with the local site via fiber optic serial lines. Several advanced control features are available in the dual arm system, such as *contour*

*following, shared compliance and harmonic motion generator* [1], [8].

3. *Controlled Light Sources* to create viewing conditions similar to those found in a space environment.

The local site of the ATOP system consists of the control room with the operator interface (fig. 2). This interface has evolved following the development and the integration of new technologies into the teleoperation system and is organized in three main subsystems:

1. A **Data Interface** consisting of:
  - (a) *Parameter acquisition* interface to enter robot configuration and control parameters.
  - (b) *Data acquisition* interface to handle the communication with the smart hand and process incoming force and torque data.
  - (c) *Programming, debugging and set up* interface for the development, monitoring and setup of the control programs for the manipulators.
  - (d) *Sensors* interface to visualize in real time force and torque data collected by the manipulators sensors.

2. A **Video Interface** composed of:

- (a) *Video Monitors*, displaying two monoscopic and one stereo views of the remote site,
- (b) *Computer Graphics Simulation*, equipped with predictive display, for time delay compensation and operator training.

3. A **Manual Interface** consisting of:

- (a) *Force Reflecting Hand Controllers (FRHC)*, driven by a pair of UMC's to command the movements of the robots and to feed back force information to the operator.
- (b) *Camera Gantry Controls*, to move the beams holding the cameras to the desired viewing position.
- (c) *Camera Controls* to adjust pan, tilt, focus, zoom and iris of the cameras.
- (d) *Foot Pedals* for the power tools in the remote site.

### III AUTOMATIC SUPERVISION

An efficient single-person teleoperation interface must perform some of the functions assigned to the operators of a multi-operator interface. To experiment with this idea, two different functions are under study: the first one is the automatic display of camera and control menus during a task, and the second is the generation of feedback messages to the operator. In the first case, the interface must automatically show the operator the appropriate command menus for the specific task's phase. In the second case, the interface must provide the operator with performance feedback messages derived from a stored model of the task execution. In both cases, a key element of these advanced tools is a program that can follow the development of a teleoperated task by segmenting the sensory data stream into appropriate phases.

A task segmentation program of this type has been implemented by means of a *Neural Network* architecture [2] and it is able to identify the segments of a *peg-in-hole* task. With this architecture, the temporal sequence of sensory data generated by the wrist sensor on the manipulators are turned into spatial patterns and a window of sensor observations is associated to the current task phase.

This problem is referred in the literature as that of *learning time sequences* and has been approached primarily with two architectures: *Time-Delay* and *Partially Recurrent* networks [5]. Partially Recurrent Networks better represent the temporal evolution of the task since they

include in the input layer a set of nodes connected to the output units, to create a context memory. These units represents the task phase already executed – *the previous state*. A set of fixed weight connections have been established among the output and context layer units (see figure 3).

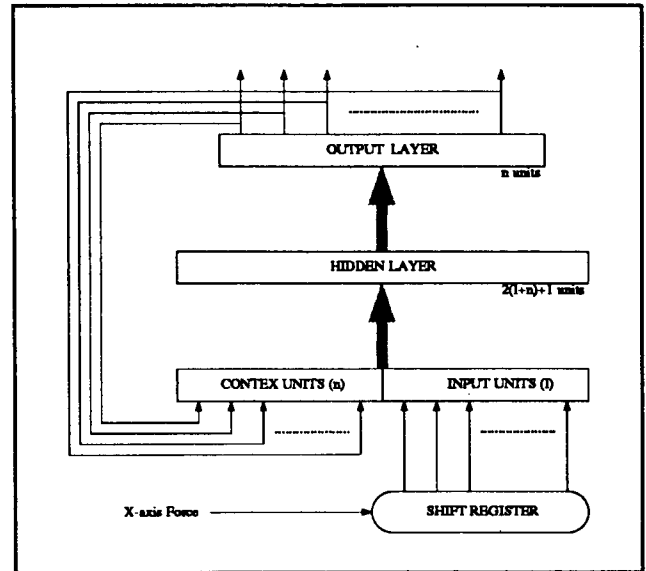


Figure 3: Partially Recurrent Neural Network

Training is carried out to associate the previous state and the window of sensor signals to the current state:

$$\sigma_1(t - \Delta t), \dots, \sigma_n(t - \Delta t), x(t - (l - 1)\Delta t), \dots, x(t) \rightarrow \sigma_1(t), \dots, \sigma_n(t)$$

where  $(\sigma_1(t), \dots, \sigma_n(t))$  is the state corresponding to the  $x$ -force sensor signal  $x(t)$ . The window length ( $l$  value) is a critical design factor.

The Partially Recurrent network gave good results both in training and in simulation and it has been interfaced to the ATOP telemanipulator system for real-time tests. The ATOP configuration is significantly different from the one used for the training data and therefore these tests also verified the robustness of the approach to hardware variations.

Figure 4 shows as a dotted line the output of the real-time segmentation performed by the network during an actual peg-in-hole task. The solid line represents the correspondence between task's phases and data. The time response of the network is evident in the lag between homologous transitions between the solid and the dotted lines and it depends primarily on the computer used to

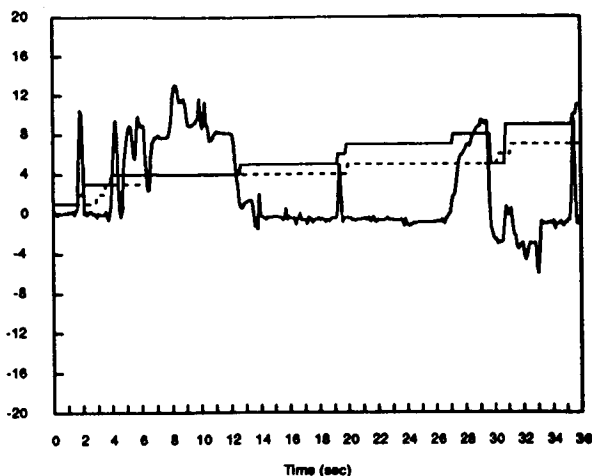


Figure 4: Segmentation in the real-time experiment

collect data and perform the network calculations. Several experiments have been carried out and the results have been quite encouraging with a percentage of correct segmentations approximately equal to 65%. Figure 4 refers to the a typical Peg-in-Hole phases' sequence [3]. Approximately at time 29 sec the network misclassifies the end of the *extract* phase (index n. 8) that should have occurred at time 34 sec. The network showed also unexpected capabilities to recover after misclassification and it was also able to follow tasks whose phases' sequence varied from the training one. During peg extraction, for example, if the operator decided to regrasp the peg, the network was sometimes able to make the transition from *extraction* to *insertion* and again to *extraction*. These tests were quite encouraging and this type of architecture can provide a building block for the automatic tools of an advanced teleoperation interface.

#### IV COOPERATIVE REDUNDANCY MANAGEMENT

For redundant manipulators it is not possible to formulate a closed form solution of the inverse kinematic problem and many control algorithms use a mixture of velocity based control and optimization procedures. The inverse Jacobian is used to compute the velocity transformations and a local optimization of some evaluation criteria is used to determine the values of the redundant joints in the arm null space [9], [6]. The above velocity-based kinematic control has several drawbacks, including computational cost, numerical instability when the Jaco-

bian inversion is performed near singularities and the lack of global optimization of the arm configurations.

To eliminate these problems, a parameterization approach has been proposed for the control of redundant manipulators [7]. The redundant joints are considered as parameters of a non-redundant manipulator for which we can obtain a closed form solution of the inverse kinematics. This approach transforms the problem of controlling a redundant arm into that of selecting optimal values for the configuration parameters, i.e. the redundant joints, along the required trajectory.

This method has computational and numerical advantages over velocity-based kinematic controls and it provides the necessary support for implementing cooperative redundancy management in teleoperation. In fact, the operator can be shown a display of the parameter space in which a surface representing a performance criterion is visualized. Every point on the surface is associated with values of the redundant joints and the operator can immediately determine the best configuration. The values of the redundant joints are the parameters that are used to compute the inverse kinematics of the associated non redundant manipulator.

More specifically, a null space manifold is formed in the parameter space with the consideration of individual joint limits, and characterized by an artificial potential field representing the performance associated with the individual null space joint configurations. A null space manifold can be easily formed by varying the parameter values within their limits, and by checking the availability of a solution through the position-based kinematic solution. The manifold can be incrementally updated and animated along the given task trajectories. The artificial potential function is then formed over the null space manifold based on a combination of several desired attributes such as proximity to joint limits, proximity to singularities, and measures of kinematic and dynamic manipulability. The potential function represents the performance criterion for the selection of the joint configuration. It can be used either automatically by the system, following a local gradient search, or manually by the operator. In this case, globally optimal joint configurations may be selected by extrapolating the variations of performance associated with the selected parameter values, or by analyzing the variation of the potential function at successive task points along the given task trajectory. In short, the parameterization method allows the visualization of manipulator internal performance through the display of potential functions in the parameter space. This provides a medium for an interactive and cooperative interface for redundant telemanipulator planning, through which the

operator can decide whether, when and how to reconfigure the arm for optimal task execution.

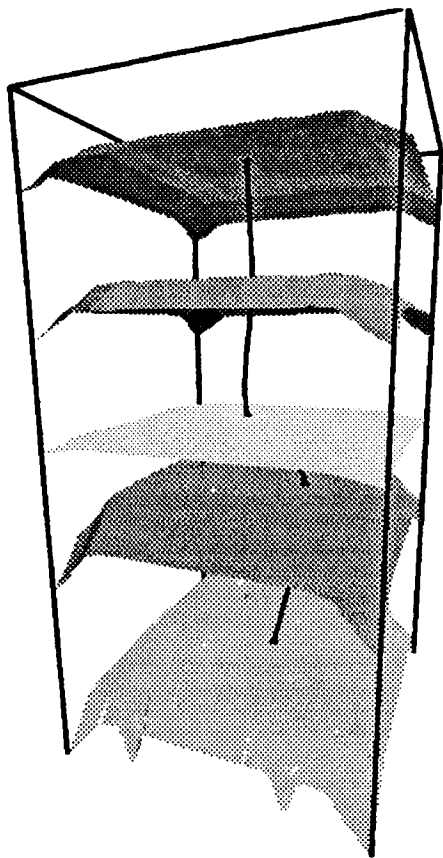


Figure 5: Criterion functions on the 2-D null space

The AAI arms used in the ATOP laboratory are decomposable arms and particularly suited for the proposed parameterization method that can be applied to each one of the two subarms in which the manipulators can be partitioned. In this case, the parameterization method is very simple because a closed form of the parameterized inverse kinematic solution can be readily obtained from each subarm and the null space manifold in the parameter space can be easily described.

The AAI arm is an 8 dof manipulator, where the 4 lower revolute joints are configured as a cascaded spherical arm for positioning and the 4 upper revolute joints are configured as a Z-X-Y-Z wrist for orientation. The AAI arm has no link offsets and since the 4 wrist axes intersect at one point, the arm is decomposable. This manipulator permits an easy kinematic control because of its zero offsets and orthogonal mechanical structure and it also

achieves a high dexterity and singularity avoidance.

The proposed parameterization method has been successfully applied to the derivation of the closed form, parameterized inverse kinematic solution of AAI manipulators. The derivation was simplified by taking advantage of this arm decomposability: the inverse position transformation uses two joints as parameters, one in the lower arm (first 4 joints) and the other in the upper arm (last 4 joints). A potential function over the solution manifold is then mapped onto the parameter space for a given task point, as illustrated in fig. 5.

In our current implementation, the operator is presented with a 3-D graphic display of the criterion functions plotted over the null space of the robot for five different end effector positions and orientations. Corresponding to each end effector position and orientation, a surface is plotted showing the value of the criterion function over the two dimensional null space. The operator can specify the weights for each criterion function for the different surfaces. The display seen by the operator is shown on Fig. 5.

The input to the program is with a graphic interface and it consists values of the redundant joints with which to start or to tune the computation of the optimal trajectory. This approach to redundant path planner offers a number of advantages to the operator for constructing feasible paths during a task. In particular, the operator has complete control in selecting the robot configuration and the process is carried out in real-time since the tool provides immediate visual feedback on the quality of the selected parameters.

## V CONCLUSIONS

In this paper we have described our current efforts to improve the communication between the operator of a telerobotic system and the system itself. The long term objective is to establish a duality between the human supervision of a telerobot, as in the supervisory control paradigm, and the automatic support to the user of an advanced teleoperator. Two main areas of research have been described. The first one aims at developing techniques for supporting the operator during task execution. The type of support envisioned within the interface will consist of task segment identification for the automatic setting of system parameters and for performance monitoring. The second research effort is concerned with the development of an interactive path planner that cooperates with the operator in the selection of the best path and configurations of a redundant telemanipulator. These automatic features will be an asset in all phases of tele-

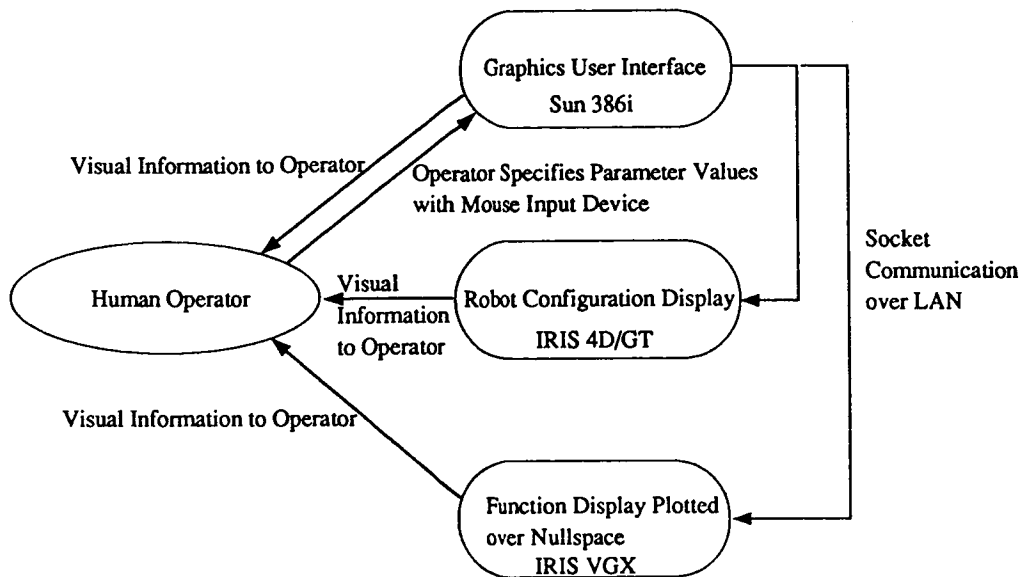


Figure 6: Operator Interaction with the Planner

operation and will be essential in supporting real teleoperated tasks.

## VI ACKNOWLEDGMENT

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## REFERENCES

- [1] A.K. Bejczy, Z. Szakaly, and W.K. Kim. A laboratory breadboard system for dual arm teleoperation. In *Third Annual Workshop on Space Operations, Automation and Robotics*, JSC, Huston, TX, July 25-27 1989. NASA Conf. Publication number 3059.
- [2] P. Fiorini et al. Neural network for off-line segmentation of teleoperation tasks. In *IEEE International Symposium on Intelligent Control (ISIC-92)*, Glasgow, Scotland, August 1992.
- [3] B. Hannaford, L. Wood, D. McAfee, and H. Zak. Performance evaluation of a six-axis generalized force-reflecting teleoperator. *IEEE Transaction on Systems, Man and Cybernetics*, 21(3), May/June 1991.
- [4] S. Hayati and S.T. Venkataraman. Design and implementation of a robot control system with traded and shared control capability. In *IEEE International Conference on Robotics and Automation*, volume 3, Scottsdale, AZ, May 14-19 1989.
- [5] J. Hertz, A. Krogh, and R.G. Palmer. *Introduction to the Theory of Neural Computation*. Addison-Wesley, Redwood City, CA, 1991.
- [6] C. A. Klein and C-H. Huang. Review of pseudo-inverse control for use with kinematically redundant manipulators. *IEEE Trans. on Systems, Man and Cybernetics*, SMC-13(3), March 1983.
- [7] S. Lee and A.K. Bejczy. Kinematic solution of 8 degree-of-freedom AAI arm. In *IEEE International Conference on Robotics and Automation*, Sacramento, CA, April 1991.
- [8] Z. Szakaly, W.K. Kim, and A.K. Bejczy. Force-reflective teleoperated system with shared and compliant control capabilities. In *NASA Conference on Space Telerobotics*, volume 4, Jet Propulsion Laboratory, Pasadena, CA, January 31 1989.
- [9] D. E. Whitney. Resolved motion rate control of manipulators and human prostheses. *IEEE Trans. on Man-Machine Systems*, MMS-10(2), June 1969.