MIT Research in Telerobotics

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This is a report of ongoing MIT research in telerobotics (vehicles capable of some autonomous sensing and manipulating, having some remote supervisory control by people) and teleoperation (vehicles for sensing and manipulating which are fully controlled remotely by people). Our laboratory has engaged in research on both human and automatic control of such manipulators and vehicles for over twenty years.

The current efforts, which are identified below by the individual graduate students doing the work, mix human and artificial intelligence/control: The first report discusses the idea of adjustable impedance at either end of pure master-slave teleoperation. The second report is concerned with simultaneous coordinated control of teleoperator/telerobotic systems which have more than six degrees of freedom (e.g., a combined vehicle and arm, each with five or six DOF). The third report briefly describes a new cable-controlled parallel link arm which offers many advantages over conventional arms for space. The fourth summarizes our work over recent years on predictor displays to compensate for time delay in teleoperator loops. The fifth report discusses the use of state estimation to help human control decisions in space. The sixth report describes ongoing research in supervisory command language. Finally, the seventh report, a composite activity of four graduate students, describes efforts to build a human "flyable" real-time dynamic computer-graphic telerobot simulator. These projects represent most, but not all, of the telerobotics research in our laboratory, supported by JPL, NASA Ames and NOAA.

1. OPERATOR ADJUSTABLE IMPEDANCE IN BILATERAL REMOTE MANIPULATION

G. Jagannath Raju

When humans manipulate objects in their environment, two senses that are extensively used are vision and the "muscle senses" that mediate kinesthesis and proprioception. Sometimes skin senses that mediate pressure and temperature are useful. The assumption made here is that the objective of the manipulation task is to identify, and/or alter the location of an object in the environment. The ultimate goal in remote manipulation would be the complete transparency of the interface, i.e., the actuators which transmit the command and the sensors that return the required information. The term "telepresence" reflects this concept of transporting the human operator not in body but in sensation to the remote location. Though the "skin senses" may be blocked by a telemanipulator mechanism and/or the telecommunication channel, the "muscle senses" and vision may be replaced with high fidelity transmission channels of vision and force/displacement. In reality owing to limitations imposed by the environment (distances, transmission medium) and technology (sensor resolution, transmission bandwidth, time delays) the transmission signals are degraded and have to be enhanced or compensated for in some way to be of real value. A force feedback channel can provide the operator with values of the force levels in the interaction with the object, displayed on a screen, or better still convert these measurements back to a force level through a servo-actuator to redirect a sense of "feel" to the operator. The force transmission channel in the forward direction transmits the forces that the human operator would have imposed on the task had she been able to manipulate the object directly. **The primary objective of this research effort is to study the effect of allowing the human operator the option to select the dynamics of the force transmission channel to suit personal muscular characteristics and the task being performed in the remote location.** The dynamics of the channel is characterized by a set of impedances. Force(F) and velocity(V) variables in mechanical systems are analogous to voltage and current signals in electrical networks, hence mechanical impedance and admittance can be defined similarly.

Nomenclature

- J, B, K : Inertia, Damping and Stiffness parameters
- T, Ω, Θ : Torque, Velocity and Position
- Z, Y : Impedance and admittance
- s : Complex frequency

Subscripts m,s,h,t refer to master, slave, human and task respectively.

For a lumped parameter model of a simple mass, dashpot, spring system, the impedance transfer function is :

$$Z(s) = \frac{F(s)}{V(s)} = Js+B+\frac{K}{s}$$

and the admittance transfer function is :

$$Y(s) = \frac{1}{Z(s)} = \frac{s}{Js^2+Bs+K}$$

Model of Master-Slave System

The sub-systems that comprise a single degree of freedom MSM system are depicted as :

A human operator manipulates a master arm/joystick to specify the desired trajectory of a slave arm in the remote location. In addition to driving the actuator of the slave arm, an actuator is used on the master arm to reflect the torque that the slave arm exerts on the environment back to the human operator. This is the force-feedback signal that the operator uses for adaptation. The three sub-systems are :

i. The human operator, who translates a given task into a trajectory of her arm, computes the forces required to achieve this trajectory, exerts these forces on the master arm, and adjusts her arm impedance and the impedances of the MSM, based on force-feedback and/or visual feedback from the remote location ;

ii. A MSM (composed of master arm and slave arm links, and master and slave servo-mechanisms) which transmits forces and motion between the human operator and the remote environment, and ;

iii. The task object in the remote environment that is being manipulated by the slave arm.

Using a linearized model the dynamics of the operator's arm can be represented by :

$$J_h \Omega_h + B(f)\Omega_h + K(f)\Theta_h = P(f) - T_{ext} = T_h(f)$$

where f is the neural firing rate ; and the admittance as :

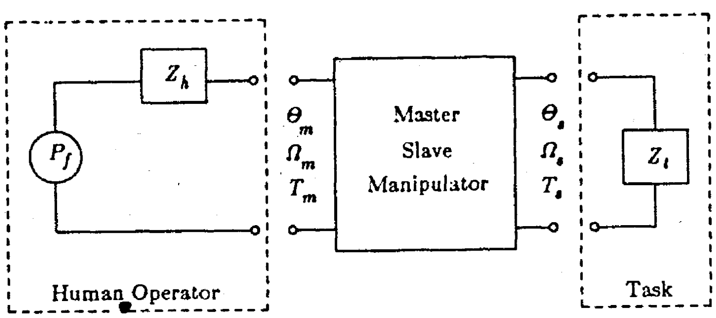
$$Y_h = \frac{1}{Z_h} = \frac{\Omega_h(s)}{T_h(f)(s)} = \frac{s}{J_h s^2 + B(f)s + K(f)}$$

The operator's arm when viewed from the master end of the MSM appears as an impedance Z_h and an effort (equivalent to voltage in electrical circuits) source $P(f)$.

A generalized mass-dashpot-spring model is used to represent the object being manipulated by the slave arm. Then its admittance can be represented as :

$$Y_t = \frac{1}{Z_t} = \frac{s}{J_t s^2 + B_t s + K_t}$$

When viewed from the slave end of the MSM, the task looks like a passive impedance Z_t.



The MSM may be modelled as a two-port mechanical system, analogous to two-port electrical networks. At the input or master port the MSM interacts with the operator, at the output or slave port with the task object in the remote environment.

The elements of the impedance matrix (z_{ij}) that characterizes the two port element can be represented as:

$$\begin{Bmatrix} T_m \\ T_s \end{Bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{Bmatrix} \Omega_m \\ \Omega_s \end{Bmatrix}$$

where

$$z_{11} = \frac{T_m}{\Omega_m}\bigg|_{\Omega_s=0}; \qquad z_{12} = \frac{T_m}{\Omega_s}\bigg|_{\Omega_m=0}; \qquad z_{21} = \frac{T_s}{\Omega_m}\bigg|_{\Omega_s=0}; \qquad z_{22} = \frac{T_s}{\Omega_s}\bigg|_{\Omega_m=0}$$

It can be shown that on combining the dynamics and the feedback (gains represented by k_{ij}) control:

$$\begin{Bmatrix} T_m(s) \\ T_s(s) \end{Bmatrix} = \begin{bmatrix} J_m s+(B_m+k_{12})+\frac{k_{11}}{s} & k_{22}+\frac{k_{21}}{s} \\ k_{14}+\frac{k_{13}}{s} & J_s s+(B_s+k_{24})+\frac{k_{23}}{s} \end{bmatrix} \begin{Bmatrix} \Omega_m(s) \\ \Omega_s(s) \end{Bmatrix}$$

Therefore by proper choice of the feedback gains k_{ij}, the elements z_{ij} can be independently modulated to match desired specifications. The impedances of the two ports of the MSM in terms of the elements z_{ij} can be expressed as :

$$Z_m = \frac{T_m(s)}{\Omega_m(s)} = z_{11} - \frac{z_{12}z_{21}}{z_{22}+Z_t}$$

$$Z_s = \frac{T_s(s)}{\Omega_s(s)} = z_{22} - \frac{z_{12}z_{21}}{z_{11}+Z_h}$$

Then given desired master and slave port impedances, Z_m and Z_s , z_{11} and z_{22} can be computed by solving the two nonlinear algebraic equations above. For a given task the human operator can adjust the port impedances by specifying desired values, and appropriate feedback gains are computed to implement the control algorithm.

One of the proposed experimental tasks emulates the action of a toggle switch with three or more stable positions. If a human were to directly operate the switch, without visual feedback, she would impose a force on the switch lever and keep increasing it till the reaction force from the switch mechanism is overcome and the switch moves to the adjacent stable position. The human senses that the switch is in the process of moving to the next position when the reaction force from the switch mechanism relaxes. The performance of the human subject in being able to shift the switch at the slave end of a one degree of freedom MSM using the master arm will be studied for different values of both master and slave port impedances. This experiment may illustrate the feasibility of allowing the human operator to adjust the MSM impedances as needed for different tasks or sub-tasks.

2. INVERSE KINEMATICS FOR REDUNDANT SYSTEMS

Hari Das

Objective

Kinematically redundant systems i.e. systems with more degrees of freedom than required for end effector specification, are studied in this project. The purpose is to obtain position of each degree of freedom for a given end effector position (a.k.a. the inverse kinematic problem). An example of a redundant system is a three link manipulator in two dimensional space where only the two coordinate position of the end point is to be specified. The system has one remaining degree of freedom after fixing the end point position.

Method

In this method, the inverse kinematics is solved by using the extra degrees of freedom to satisfy physical constraints such as obtaining desired manipulator configurations or avoiding obstacles. The method is to simulate a dynamically simple but kinematically equivalent system. Since the kinematics involves only geometry, any convient dynamics may be chosen for the simulation. Forces are made to act on this simple system to drive the end point to the desired end position. Constraints such as a prefered manipulator shape is obtained by applying torques on each joint proportional to the difference between the actual and desired joint angle. Obstacle avoidance is achieved by having repulsive forces act between obstacles and each joint of the manipulator. Advantages of this method are that a human user can interactively choose solutions in a physically intuitive way. With this method, the manipulator end effector could be kept within the viewing range of a video camera or could be kept within the range of its joint motion.

Work Done

A number of variations of the algorithm using first and second order dynamics have been attempted on a three link manipulator in two dimensional space. Also studied were techniques to speed up computation and insure stability. A number of control algorithms for computation of force at the manipulator end point and obstacle-manipulator repulsion were investigated. Convergence to desirable solutions, numerical stability of the simulation and computation time were the criteria used to compare the different variations. The most promising of these is a first order simulation using a control law on the manipulator that has a force from the tip of the manipulator to the desired end position and has all other constraints on the motion of the manipulator projected onto the nullspace of its jacobian thereby not affecting the end point motion. Trial runs with this variation on a ten link manipulator in two dimensional space have been done. The figure below shows the graphical output of the program with the ten link manipulator at the start and end of a simulation where a desired end point trajectory through the obstacles and obstacle positions were fed to the algorithm. (This might be done by a human operator in the context of controlling a manipulator arm.)

Further Work

The difference equations in the digital implementation of the simulation must be studied for a complete numerical stability analysis. The method is to be applied to other redundant systems, for example, a vehicle-manipulator system. As a part of this research, a comparison between this method and other more conventional techniques is planned.

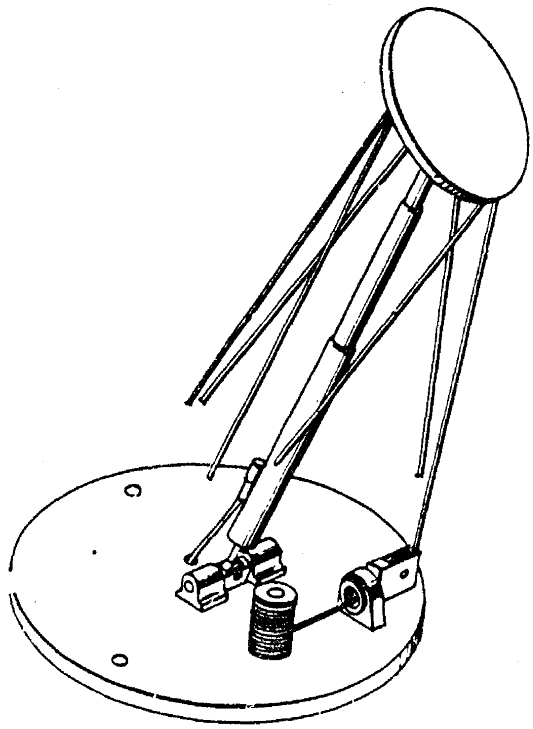
3. CABLE-CONTROLLED PARALLEL-LINK MANIPULATOR

Samuel E. Landsberger

A new kinematic design for a six DOF parallel-link manipulator arm has been designed and built and has undergone preliminary tests. It demonstrates the following advantages over conventional serial-link arms: (1) higher stiffness-to-weight ratios, because no bending members are required; (2) higher end-point force capability because links act in parallel; (3) all actuators are mounted on the base, thereby reducing inertia by a large factor; (4) inertial properties are invariant with respect to position; (5) cable capstan drive eliminates gear and joint backlash; (6) all six cable and actuator subsystems are identical, making manufacture cheaper; (7) cable links and spine collapse to a small rest-size; (8) the compressive spine can be preset to any desired compliance, or its compliance can be adjusted within the task execution cycle, (4) the forward loop specification of actuator position, given desired end-point position, is an easy calculation and does not require inverting a jacobian.

Disadvantages relative to a serial link manipulator are: (1) the arm cannot "bend around" objects; (2) the arm's strength deteriorates at greater than 45 degrees from the symmetry (vertical spine in the figure) position; (3) "wrist" rotation is limited to about fifty degrees.

Computer synthesis of path (continuous determination of cable length) is presently achieved by dividing the desired path into sufficiently small, equally spaced intervals in radius-longitude-inclination space to keep the path smooth and within bounds. Present computational steps are approximately 0.1 inches part, yielding a speed of about 100 inches per second.



Cable controlled parallel link manipulator

Analog or digital filtering to smooth out commands as well as various mechanical changes are being considered. Further performance testing with regard to bandwidth, acceleration and load characteristics, accuracy and slow speed characteristics is being done.

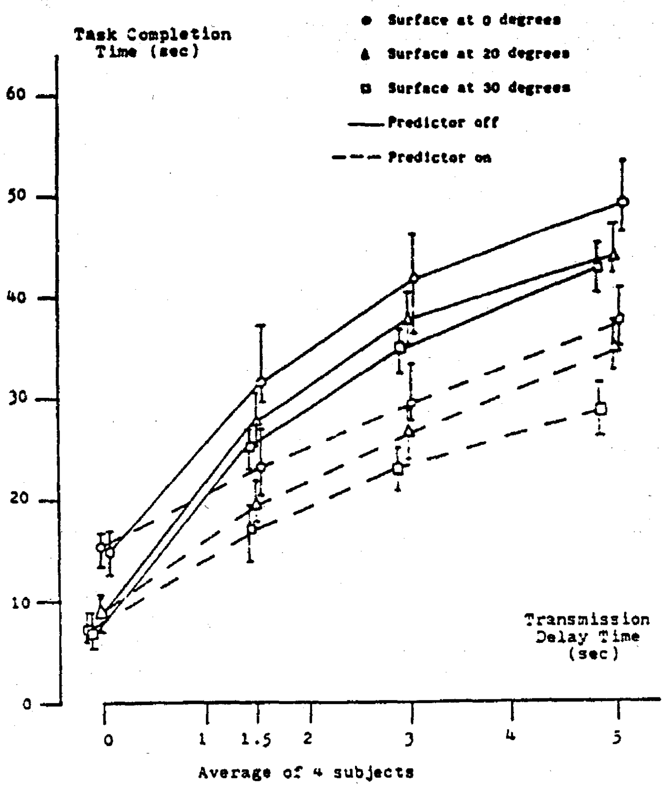
4. PREDICTOR DISPLAY COMPENSATION FOR TIME DELAY

Forrest Buzan

It has long been appreciated that time delay in a control loop produces instability. Experiments by W.R. Ferrell in our laboratory in 1965 resulted in a model predicting the number of discrete "open loop move, wait for feedback" cycles as a function of time delay and accuracy requirements of the task components. He showed that it is essentially not possible to have delayed force feedback to the same hand as is controlling a master-slave teleoperator and avoid instability.

Recent developments in fast "frame grabber" video technology have enabled the development of a predictor display wherein the human operator's control signals drive a kinematic model of the manipulator: this superposes on the delayed video display a "stick-figure model" which, because it is instantaneous, "leads" the video image of the manipulator arm. This is illustrated in the figure below.

A series of experiments has demonstrated the efficacy of the predictor display. First experiments by M. Noyes used the predictor in two tasks, a tracking task and a task involving picking up blocks and dropping them into a box. There were nine treatments: 1 - 4 used a predictor display while 5 - 8 did not. Treatments 1 - 8 had a 1.8 second time delay where in 1, 2, 7, 8 it was continuously refreshed; in 3, 4, 5, 6 it was buffered to present same-time frame snapshots. Resolution was high in 1, 3, 5, 7; it was low in 2, 4, 6, 8. Treatment 9 had no predictor, no delay and high resolution. Noyes' results shown below (means of four subjects) indicate a major advantage with the predictor.



Mar's results

5. AIDING HUMAN OPERATORS WITH STATE ESTIMATES

James B. Roseborough

There are many situations where it would be desirable to have computer based estimates of process states to augment an operator's own personal estimates when making decisions. Possible applications of this are in space, where the process is a tumbling satellite which the operator must retrieve, and undersea navigation where the operator must navigate successfully in an unfamiliar environment. The computer based aid may be used to "track" the satellite or the environment, predict future states of the process to help in planning, and possibly present alternate views of the process to the operator which would not normally be available.

One of the problems with simply providing state estimates is that there may be too much information for the operator to cope with effectively. It is therefore important to examine what simplifications human operators tacitly use when they are presented state information, and which of these may be built into the decision making system to ease the job of the operator with negligible loss in system performance. This work concerns itself with building a simulation of a satellite recovery task, providing a decision aiding system based on process state estimation, and examining the simplification issues with respect to this task.

Satellite Recovery Task

A simulator is under construction which will include two satellites in orbit around the earth. One of these is a target of recovery, and it will be experiencing an arbitrary rotation initially without force or torque disturbances. The other satellite is a shuttle which the operator must position so as to fetch the target. The view from the shuttle of the target, stars, and the earth will be displayed to the operator, as will other information which might normally be available about the state of the shuttle and the target. The goal of the task is to slow or stop the rotation of the target, or to successfully plan actions so it may be grabbed with a robotic arm.

Although the mathematical description of rigid body rotation in three dimensions is straightforward and entirely deterministic, the observed behavior can appear to be quite complex and unpredictable. The decision aiding system will therefore incorporate a model of the rotating target, and the human will provide data to the model as follows. A video frame may be taken at any time, and the operator will input the screen locations of certain agreed upon reference points. After several frames have been processed in this way, the computer will have a refined estimate of the process state. A sufficiently refined state estimate can be used to estimates future states of the target for planning.

Some Numerical Considerations

We assume that the process state can be specified as a set of unknown values θ_1 through θ_n. The structure of the process is well enough specified that any set of values $\{\theta_1, \cdots, \theta_n\}$ for $t=t_0$ uniquely determines the $\{\theta_1, \cdots, \theta_n\}$ for $t>t_0$. This is equivalent to saying that there is some function $\Phi: \theta(t) \longrightarrow \theta(t+dt)$.
The function Φ describes the dynamic behavior of the process of interest. For the satellite example, the states of the process are the linear and angular positions and velocities of the satellite, and possibly some geometric or inertial parameters if they are not precisely known ahead of time. The Φ function is a model of the process dynamics, so it would be normal to choose Φ to correspond to the equations of motion for a rigid body.

In addition to the function Φ which represents the process dynamics, there must be an additional function $\Psi: \theta(t) \longrightarrow \zeta(t)$ which relates the states of the plant to observables. Again for the satellite example, the observables are the (x,y) coordinate pairs of reference points as they appear on the video screen, and the mapping Ψ expresses the relationship between the satellite's position in space and the location of the satellite as it appears on the monitor screen.

Considering only the problem of state estimation, there are approximately twelve state variables which will fully desribe the state of the target, and twelve more to describe the state of the shuttle. Assuming that shuttle state information is available to a high degree of accuracy, we can consider these latter variables as known and the problem reduces to that of estimating the values of twelve unknown target state variables. For each video frame which is taken and each reference point recorded, two values are provided, so a minimum of six reference point locations is needed to establish the state. Since the velocity information cannot be derived from a single frame, at least two frames of data must be taken. Additionally, the measurement process itself will contain noise, so more points than the absolute minimum should be used to achieve a better estimate.

Algorithms such as the extended Kalman filter algorithm or stochastic approximation methods may be used to perform the state estimates. A significant feature of these methods is that error estimates are provided in addition to the point estimate of state. It is a major purpose of this work to determine of what use the additional information may be to a human operator, or if it is of any use whatsoever.

Progress to Date

Previous work has indicated that when humans are presented with state estimates for a specially constructed experimental task, they make simplifications to it before using it in their decision process. "Partitioning" occurs when a distribution over a large number of possible values of a state variable is reduced to one over fewer possible values. For example, the reduced set of possible values could be "hot," "medium," and "cold." "Point estimates" of states are single values derived from a distribution over possible values. "Focus" refers to concentrating on the values of a single state variable while ignoring the information relating to another state variable. Experimental evidence has been gathered to indicate that people will use each of these simplifications, and their role in the satellite retrieval task must be examined.

A simulator has been constructed which includes a shuttle and a target spacecraft. A numerically stable simulation is achieved by separating the motion of a nominal, orbiting reference frame from the motion of the bodies within the reference frame. The simulation of the dynamics of rigid bodies in the non-inertial, orbiting reference frame must, of course, include effects due to the rotating reference frame, and the non-uniform gravity field.

The simulation of rigid body rotation is usually accomplished by using euler angles to represent the angular position of the body. This is a straightforward and practical method for simulations of, say, robotic arms, where good simulations are required only for short periods of time and angular excursions are limited. In the case of a tumbling body, the simulation must be accurate and stable over long periods, and arbitrary rotations must be allowed. These two goals are difficult to achieve using a standard euler angle approach. This problem is solved using the angular momentum vector and a rotation matrix directly as state variables. Using this method, simple second order euler integration yields very satisfactory results over a long simulation period.

A third interesting area is the direct recovery of velocity information from successive frames through image processing techniques. In this approach, the operator would indicate reference point locations as before, and he would also indicate a region in the image where velocity processing is to take place. Results in this area are preliminary.

Conclusions

A simulator is under construction which allows subjects to "fly" a spacecraft to a tumbling target satellite and retrieve it. Because of the nature of the information involved, a decision aiding system will almost certainly be useful in such a task. Some details relating to the simulator and state estimator have been worked out, and a few more remain before the research will be complete. It remains to be determined what simplifications of the state information are useful and appropriate to apply in this task. The results of previous experimentation regarding simplification of state information by humans will be applied as it is possible to do so.

6. A COMMAND LANGUAGE FOR TELEMANIPULATION

Wael Yared

General Approach

To qualify as an intelligent autonomous system, a command language for manipulators in a supervisory control situation must include two distinct components: knowledge of the task at hand, and a systematic scheme of man- machine interaction .

I am approaching the problem of designing a supervisory command language from a computational-linguistic point of view. In a first phase, a conventional, domain-specific natural language interface is being developed and implemented on a computer simulation. The simulation brings into play a graphic representation of a manipulator arm in a specific task environment with obstacles, and an operator. The operator types task-level descriptions to the robot both of the environment and of the task itself. In a realistic situation an accurate description of the environment could be provided by CAD-like databases, and a rough outline of the obstacles by purposely vague linguistic descriptions quantified graphically using a fuzzy set calculus. Task planning is then carried out interactively, in a mixed-initiative dialogue with the operator playing a supervisory role. This constitutes the second phase of the research, where the emphasis will be placed on developing different grammars of discourse corresponding to the different structures of task-instruction dialogues.

The Natural Language Interface

A natural language interface is a necessity if one wants to exploit the vagueness inherent to human language. The scheme that has been adopted here is a simplified, context-sensitive grammar of English implemented using Augmented Transition Networks. The arcs in these networks embody syntactic features (such as noun phrases, prepositional phrases, etc.) as well as features more commonly identified with semantic grammars (which are, in this implementation, features such as physical attributes of objects and obstacles in the environment). A new type of arc has been defined for "hedges", or linguistic modifiers, which operate on physical object attributes and are quantified by fuzzy set membership functions. Extra-linguistic information such as pointing is also supported in this application. No pragmatics is incorporated at this level, as this knowledge is relegated to the discourse grammar.

The Discourse Grammar

Research in discourse structure is a conceptual outgrowth of sentential linguistics. Researchers in the field have first attempted to find internal representations of utterances that are amenable to computational manipulation; this internal representation is usually the result of mapping from a parsed representation of a sentence to an expression in "logical form". The logical extension of that work is the linking of such discourse entities, in other words developing some bookkeeping system (in the form of a pushdown stack for example) that stores and updates the successive "foci" of discourse, with an ability to point back to previous utterances.

A practical discourse grammar can then be specified in the form of an Augmented Transition Network just like a regular grammar with the basic unit of analysis being, instead of the word, an utterance or a set of utterances. States and arcs in this network are written in terms of functional discourse relations (for example setting up a sub-topic of discourse, resuming a higher conversational level). From each state, the set of arcs leaving that state represents the conversational "moves" available to the conversational participant. The tests and registers, just like in a sentence ATN, are used to track the dynamic aspects of the discourse -the stack of foci. Finally, the actions on arcs serve to update the current focus of conversation.

This is a first attempt at systemizing man-machine interaction. It benefits from the linguistic planning ability of a skilled human operator to build up a task plan for the robot, and is particularly well-adapted to "structured" tasks, such as the assembly or dissembly of a piece of equipment (a pump motor, say), but could conceivably be extended to less obvious situations as well. Experiments will be performed on transcripts of expert/apprentice instructional dialogues for various tasks in view of eliciting an underlying structure.

7. DEVELOPMENT OF HUMAN-FLYABLE, REAL-TIME DYNAMIC COMPUTER-GRAPHIC SIMULATOR

Chi-Cheng Cheng, Kan Chin, and Patrick Judd

In this project we are providing, on a Silicon Graphics IRIS workstation, a vehicle, manipulator arm and environment, all realistically desplayed in real time with hidden surface removal. The vehicle has realistic dynamics and is controlled by a six-axis force-joystick. The manipulator arm has only kinematics represented; it is controllable either by a second six-axis force-joystick or by a six DOF master arm. The manipulator and end effector will be capable of grasping simple objects. A vehicle control panel is also displayed on the computer screen.

One version of this simulation has a capability for running repeated "test trials" with different control movements, recording the trajectory as well as the control inputs for each trial, and then having the "best" command trajectory fed to the "actual" teleoperator to reproduce in reality the trajectory selected from the simulation. This technique, it seems to us, offers many possibilities as a simple adjunct to a telerobot.