An Architecture to Support Teleoperation and Autonomy

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The Flight Telerobotic Servicer (FTS) will support assembly and maintenance activities for the Space Station. In order for the FTS to evolve with technology, careful attention must be paid to the system's functional architecture. This paper describes an approach to the functional architecture so that teleoperation, slated for beginning of the program, and autonomy, scheduled later in the program, can both be supported. The system is hierarchically organized where task decomposition, world modeling, and sensory processing are explicitly represented. Goals at each level of the hierarchy are decomposed spatially and temporally into simpler tasks which become goals for lower levels. The spatial decomposition facilitates control and coordination of multi- arm robots.

1. INTRODUCTION

NASA has embarked on a serious program of research and development in anticipation of the robotics requirements for the Space Station [1]. Robot related research is currently in progress at many centers [2-6] such as Langley, Oak Ridge National Labs, the Jet Propulsion Laboratory, Ames Research Center, Johnson Space Center, etc. Since the FTS is targeted for use in the assembly and maintenance of the Space Station, the envisioned FTS will need multiple manipulators, vision and other sensory processing, world modeling, planning, etc., in order to adequately perform its functions.

The NASA program for the development of the FTS expects to use teleoperation for the short term with autonomy blending into the control structure gradually as technology advances. In this way, the probability of success for the FTS is enhanced. This presents certain architectural problems, however. If the FTS is to evolve from teleoperation toward autonomy, the control system architecture must be able to support the transition.

Evolving primarily from work done on automated factories [7], NBS has developed a hierarchically organized control system. The NASA/NBS Standard Reference Model for Telerobot Control System *Architecture* (NASREM) [8] has been adopted by NASA for use as the model for the FTS control system. This architecture, which is actually comprised of the three hierarchies of task decomposition, world modeling, and sensory processing, supports the spectrun of control from total teleoperation to total autonomy.

The NASREM architecture is presented in this paper. It is shown how multiple robot arm control and coordination is supported by illustrating the interactions required between task decomposition and the world model for two specific levels of the NASREM hierarchy.

2. NASREM ARCHITECTURE

The FTS will begin with teleoperator control where a human is an integral part of the control loop. Eventually, the mode of operation will become autonomous where the human gives the robot commands to be executed and the robot reports back when the task is completed. In order to start with teleoperated control and evolve toward autonomous control without a complete redesign of the robot control system, serious thought must be given to the control architecture to be sure that the system has the ability to be easily modified as technological advances occur.

The NASREM functional architecture for the control system is shown in Figure 1. The control system architecture is actually composed of three hierarchies: task decomposition, world modeling, and sensory processing. The task decomposition hierarchy modules perform real-time planning and task monitoring functions. They decompose task goals in terms of both space and time. The sensory processing hierarchy supplies information about the environment to the world model. This involves the processing of

sensory data so that patterns, features, events, etc., can be measured about the external world. The modules of the world model perform two functions. First, the world model contains the best estimate of the state of the external world. This can be used to answer queries, make predictions, and reason about the objects in the world. Second, the world model acts as the interface between the task decomposition and sensory processing hierarchies. This promotes greater modularity both in function and implementation. For example, in the execution of a particular goal, the task decomposition module may request the location of a certain object in the environment from the world model. The best estimate of the object location is returned immediately. The task decomposition neither knows nor cares which sensors were used determine the object location. It only matters that the best estimate is returned with minimal time delay.

2.1. Task Decomposition Hierarchy

The task decomposition modules plan and execute the decomposition of high level goals into low level actions. Task decomposition involves both a temporal decomposition where the goal is broken up into a sequence of actions along the time line and a spatial decomposition where concurrent actions are executed by different subsystems. Each task decomposition module at each level of the hierarchy consists of a job assignment manager JA, a set of planners PL(i), and a set of executors EX(i). These decompose the input task into both spatially and temporally distinct subtasks as shown in Figure 2.

2.2. World Modeling Hierarchy

The world modeling modules model and evaluate the state of the world. The world model is the system's best estimate and evaluation of the history, current state, and possible future states of the world, including the states of the system being controlled. The world model, as shown in Figure 3, performs the following functions:

1. Maintains the data in the world model by accepting information from the sensory system. This keeps the model of the world in registration with the physical world.

2. Provides predictions of expected sensory input to the corresponding sensory processing modules based on the state of the task and estimates of the external world.

3. Answers "What if?" questions asked by the planners in the corresponding level task decomposition modules. The world modeling modules evaluate the results of hypothesized actions.

4. Answers "What is?" questions asked by the executors in the corresponding level task decomposition modules. The task executor can request the values of any system variable.

2.3. Sensory Processing Hierarchy

The sensory processing hierarchy modules recognizes patterns, detects events, filters and integrates sensory information over space and time, and reports this information to the world model to keep it in registration with the external world. At each level, sensory processing modules compare world model predictions with sensory observations and compute correlation and difference functions. These are integrated over time and space so as to fuse sensory information from multiple sources over extended time intervals as shown in Figure 4.

2.4. Operator Interface

The control architecture supports an operator interface at each level in the hierarchy. The operator interface provides a means by which human operators, either in the space station or on the ground, can control, observe, or supervise the telerobot. Each level of the task decomposition hierarchy provides an interface where the human operator can assume control. The task commands into any level can be derived either from the higher level task decomposition module, from the operator interface, or from some combination of each. Using a variety of input devices such as a joystick, mouse, trackball, light pen, keyboard, voice input, etc., a human operator can enter the control hierarchy at any level at any time of his choosing to monitor a process, to insert information, to interrupt automatic operation and take control of the task being performed, or to apply human intelligence to sensory processing or world modeling functions. Table 1 illustrates the types of interaction an operator may have at each level.

3. MULTI-ARM CONTROL

Multiple manipulators have been used for many years time in teleoperated mode for such applications in the nuclear industry. Originally, the masters and slaves were coupled mechanically but technology now supports an electronic interconnection. The system is able to remain stable in teleoperated mode because the operator has some force feedback from the manipulator. Traditionally, this has been done by force reflection which can be implemented in several ways [9]. It becomes quite challenging to control multiple robots autonomously rather than by teleoperation.

Freund [10] considered the problem of two independent robots working in the same workspace. His work was mainly concerned with avoiding collision between independent robots. He used a hierarchically organized nonlinear control technique with an accurate model of the robot dynamics to plan the trajectories for both robots simultaneously. While collision avoidance is certainly important, his work did not address the problem of cooperation between two robots executing a task.
The automatic control of coordinated multiple manipulators presents a subtle difficulty because even with relatively small position errors, very large forces can be generated

when closed kinematic chains are formed. Luh [11] suggested an approach where one robot acts as the leader while the other robot acts as a follower. The desired motion of the leader is planned based on the desired motion of the object. Given the state variables of the leader, which include joint positions, velocities, forces, etc., the holonomic constraints on the position and orientation of the follower can be calculated in real time and used for control.

An approach to multiple arm coordination can be implemented using the NASREM architecture. Hierarchically organized multi-arm coordinated control starts at the task level as illustrated in Figure 5. Suppose that the task is to move object O to position P. The job assigner (JA) for the task level first determines which type of motion strategy is most appropriate: single arm, dual arm, etc., by suggesting to the world model the various alternatives and then choosing the best evaluation score. The evaluation of a specific strategy can be based on the weight of the object, the location of legal grip points, etc. The job assigner also designates the leader and follower arms.

At this point, the planners (PL) in the task level for the leader and follower are accessing the world model to determine which gripper is required for the part and the precise location of each robot's grasp point. The executors (EX) at this level need information about the current gripper on the robot in order to send out the proper sequence of E-Moves (elementary movements) required to perform the task. This decomposition continues through the e-move and primitive with two parallel chains of control, one for each robot. Each chain, however, has a slightly different method of execution because one robot has been designated to be the leader and the other the follower.

At the servo level, following Luh's algorithm, the leader is operating in the mode of simple position control. The only difference between the leader's activities for coordinated activity and independent activity is watching the world model to wait until the follower robot is in the correct state. The follower, however, operates quite differently. The follower, illustrated in Figure 6, is constantly interrogating the world model for its current position and forces. The world model also is needed to provide the position and forces generated by the leader robot. These are combined in the motion control algorithm to effect coordinated movement.

This approach is only one way in which coordinated robot control can be performed. By changing the algorithms in the servo level or any other level, different strategies for dual arm motion control can be compared and contrasted for different applications.

4. CONCLUSIONS

The use of two arms in robot tasks opens up new research areas in space as well as terrestrial applications. A standard reference model architecture was presented which supports the evolution of robot control from teleoperation to autonomy. Using the NASREM architecture, it was shown how multiple armed robots could be coordinated in the execution of the task of free space motion.

5. REFERENCES

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TABLE I -- OPERATOR INTERACTION AT EACH LEVEL

LEVEL	TYPE OF INTERACTION
At the servo	replica master, individual joint position, rate, or force controllers.
above servo	joy stick to perform resolved motion force/rate control
above prim	indicate safe motion pathways. Robot computes dynamically efficient movements
above e-move	graphically or symbolically define key poses. menus to choose elemental moves.
above task	specify tasks to be performed on objects.
above bay	reassign telerobots to different service bays. insert, modify, and monitor plans describing servicing task sequences.
above mission	reconfigure servicing mission priorities.

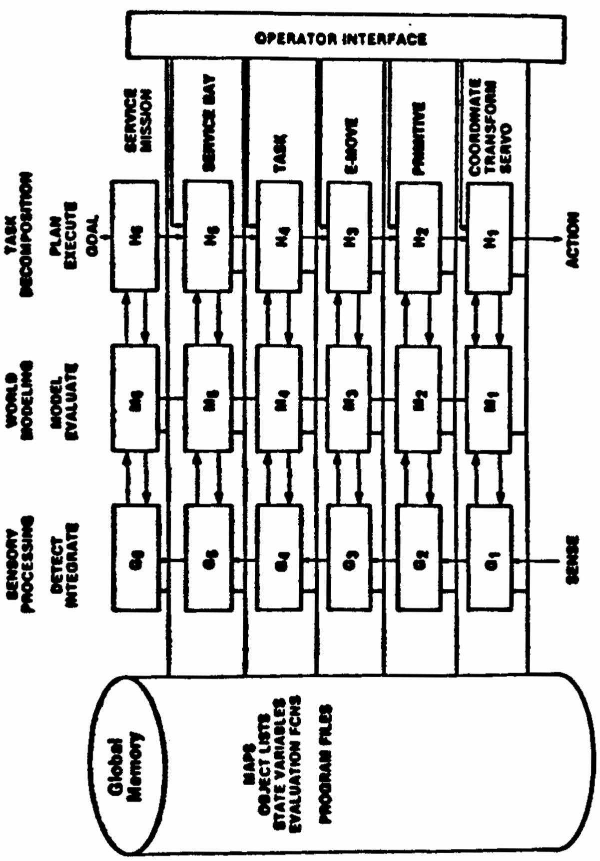

FIGURE 1 : A Hierarchical Control System Architecture for Telerobots.

Task Decomposition

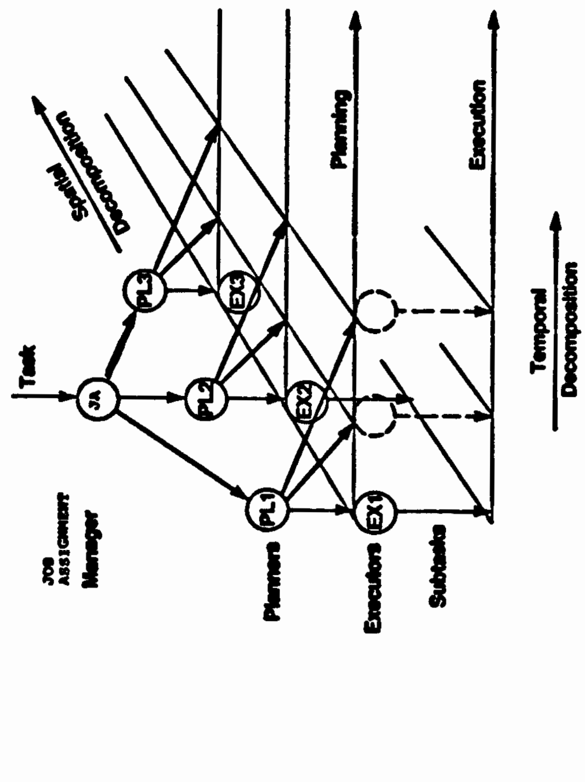

FIGURE 2: The job assignment JA performs a spatial decomposition of the task. The planners PL (j) and executors EX (j) perform a temporal decomposition.

World Modeling

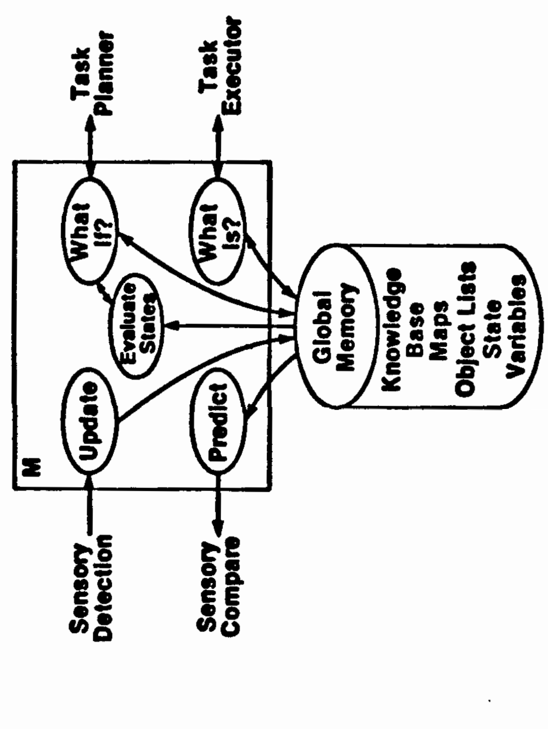

FIGURE 3: Functions Performed by M Modules in the World Model.

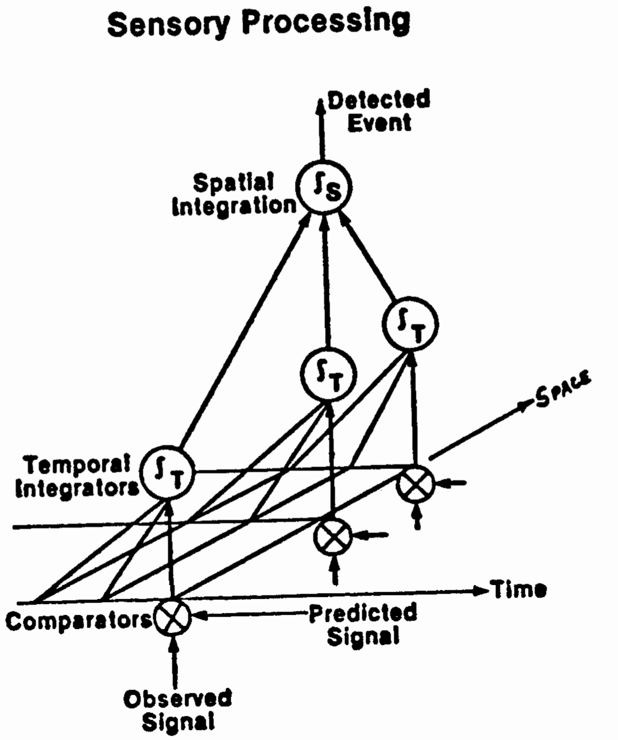

FIGURE 4: Each sensory processing G Modules performs a comparison and both temporal and spatial integration.

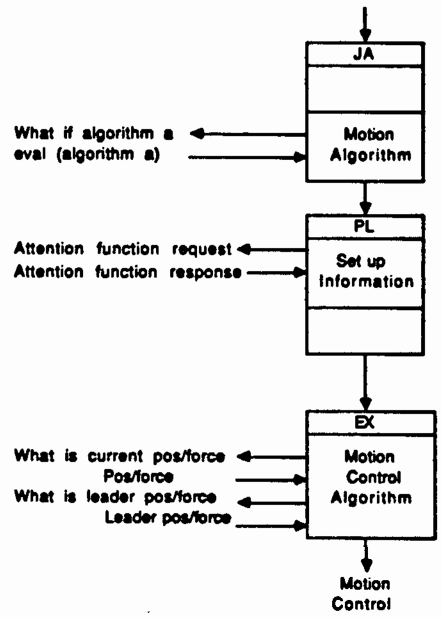

FIGURE 6: Servo Level of NASREM Task Decomposition Hierarchy for Follower.

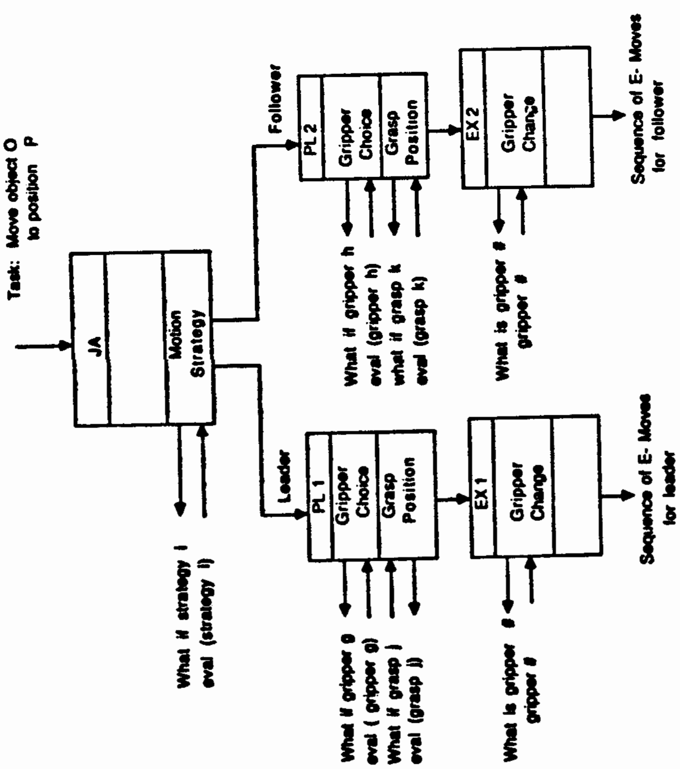

FIGURE 5: Task Level of NASREM Task Decomposition Hierarchy.