ANL/TD/CP-105653

Perceptual Basis for Reactive Teleportation

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2001 SPIW International Symposium
on Intelligent System and Advanced Manufacturing: Conference on Smart Optomechatronics Systems

October 28 – November 2, 2001
Boston, MA

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ABSTRACT

To enhance task performance in partially structured environment, enhancement of teleoperation was proposed by introducing autonomous behaviors. Such autonomy is implemented based on reactive robotic architecture, where reactive motor agents that directly couples sensory inputs and motor actions become the building blocks. To this end, presented in this paper is a perceptual basis for the motor agents. The perceptual basis consists of perceptual agents that extracts environmental information from a structured light vision system and provide action oriented perception for the corresponding motor agents. Rather than performing general scene reconstruction, a perceptual agent directly provides the motion reference for the motor behavior. Various sensory mechanisms - sensor fission, fusion, and fashion - becomes basic building blocks of the perception process. Since perception is a process deeply intertwined with the motor actions, active perception may also incorporate motor behaviors as an integral perceptual process.

Keywords: teleoperation, structured light system, reactive behavioral agent, action oriented perception

1. INTRODUCTION

For tasks in unstructured and unpredictable environment, teleoperation is widely adopted as a practical alternative to the autonomous robots. Due to the radioactive environment, operation, repair and dismantling of nuclear facilities present large potential demands for telerobotic technologies. Although teleoperation is the most flexible form of robot operation, it is known to be inefficient and imprecise. Our experience of using a dual-arm robot system (Figure 1) to remotely manipulate various tools for nuclear facility D&D (decontamination and dismantling) revealed that 90% of the operation time is wasted for aligning tools, rather than performing the actual tooling operation. What is required is a more efficient form of teleoperation which combines sensor-based automatic operation and manual teleoperation. Such a semi-automatic teleoperation is particularly suited for the D&D applications because most nuclear facilities are not entirely unstructured environment - much of the environmental geometry and the components shapes are known in advance. In the semi-automatic teleoperation, human operator directs the gross motion of the robot arm, leaving the robot's reactive autonomy to complete precise alignment of the tool.

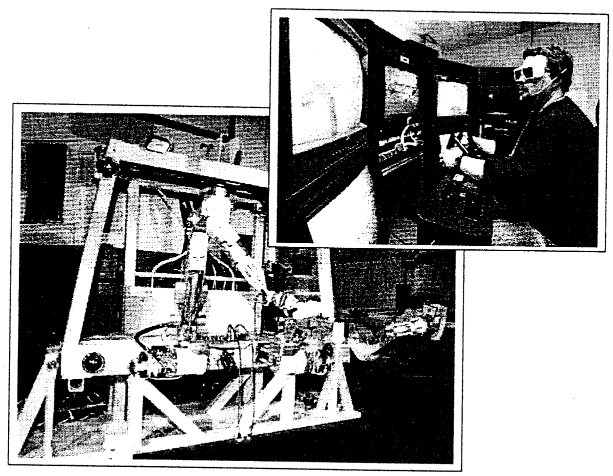


Figure 1. Teleoperated dual-arm manipulator

Robot control system can be designed as deliberative system or reactive system. Compared to the conventional deliberative system, the reactive system provides more flexibility and is more suitable for tasks in unpredictable environment. Also, because the reactive robotic architecture is built in bottom-up fashion with independent behavioral agents as building blocks, it supports incremental competency in the development phase; i.e. than the entire system needs to be completed before testing is feasible. Due to such advantages, a research effort had been made to facilitate partially automated teleoperation for D&D tasks based on reactive robotic architecture[1]. In this schema based approach, two types of reactive agents are developed, respectively for motion behavior and perceptual behaviors. In implementation, motor agents were encoded as mathematical functions describing the tool motion vector, and the resultant robot motion was determined through vector sum. For such simple and purely reactive motor agents, the perceptual agents are degenerated to simply dispatching the results of image preprocessing - sensor fission. However, as more becomes known about the environment and the tasks, more complex motor behaviors can be constituted to further improve task efficiency. For such compound system, more complex perceptual behaviors are required. In this paper, perceptual behaviors are presented for a few types of compound motor behaviors in reactive teleoperation. Various sensory mechanisms - sensor fission, fusion, and fashion - are the basic building blocks of the perception process. Furthermore, since perception is a process deeply intertwined with the motor actions, some active perception also incorporate motor behaviors as an integral perceptual process.

2. REACTIVE BEHAVIORS FOR SEMI-AUTOMATIC TELEOPERATION

2.1. Reactive Robotic Architecture

A reactive telerobotic control system has been composed based on schema-based robotic architecture[2]. Here, the robotic architecture refers to software architecture, rather than the hardware side of the system. As shown in Figure 2, this reactive robotic architecture is composed from assemblages of motor-behavioral agents, which tightly links sensory input to motor actions. Embedded within each motor agent is a perceptual agent that provides environmental information immediately related to the behavior which decides an action. The output motion commands of each motor schema behaviors are then coordinated through weighted vector summations. This behavioral coordination also correlate human intervention with sensor-based autonomous operation, and constitutes control system for semi-automatic teleoperation.

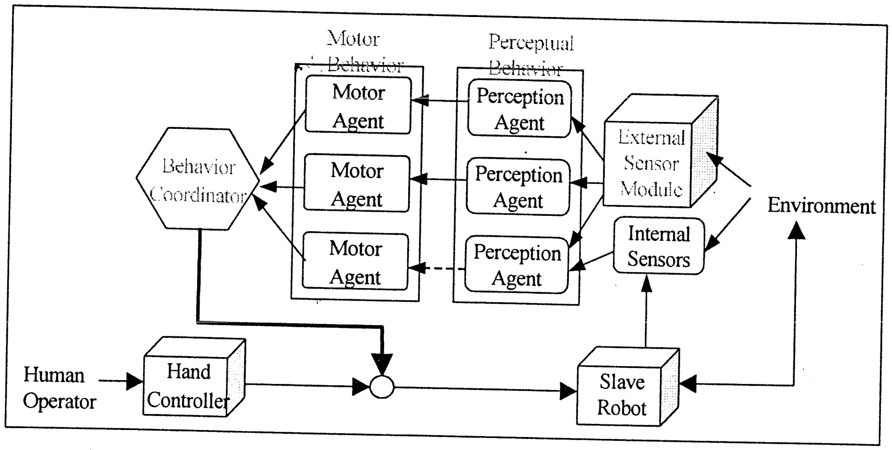


Figure 2. Reactive architecture for semi-automatic teleoperation

2.2. Motor behaviors in D&D tasks

Our experience in robot operations revealed that most D&D tasks are composed of a few large grain motor behaviors as shown in figure 3. Such high-level behaviors can be assembled from a few primitive reactive behaviors. The characteristics of these motor behavioral assemblages are described as following.

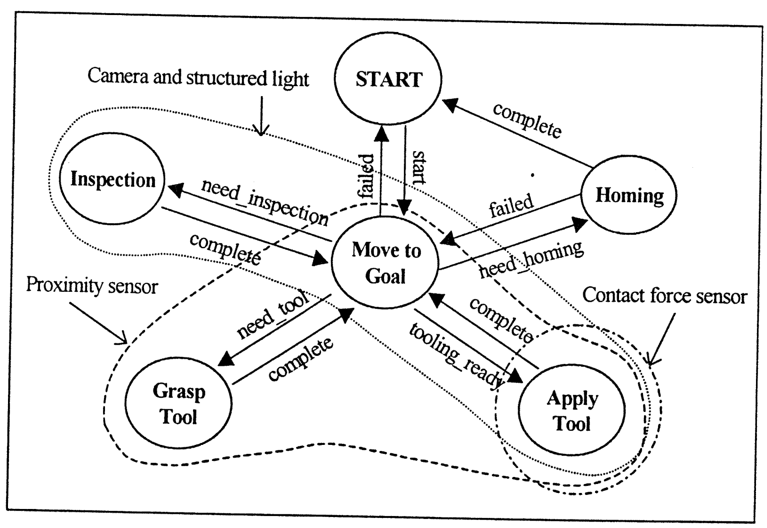


Figure 3. Motor behaviors for D&D teleoperation

Move_to_goal moves the end-effector to a goal location. As can be seen in Figure 3, this behavior provides preliminary motions in between various tasks, which require transporting the tools. As shown in the finite state diagram of Figure 4, it is constituted by a sequencing the actions of the following three motor agents.

gross_move_forward: Whenever the presence of a certain landmark pattern is recognized, the robot will move the end-effector move toward the landmark.

mid_range_tracking: This behavior is triggered whenever the presence of a certain landmark pattern is recognized and the distance to the landmark is within certain range. The robot will move the end-effector toward the landmark, and while aligning the end-effector orientation in accordance with the geometric shape of the target workpiece. Also, the trajectory is further modified to avoid obstacles.

close_range_docking: When the robot is too close to the target workpiece, camera system is no longer useful. When this condition is recognized by the proximity sensor, the robot moves its end-effector slowly in the surface normal direction of the workpiece until the end-effector touches the workpiece.

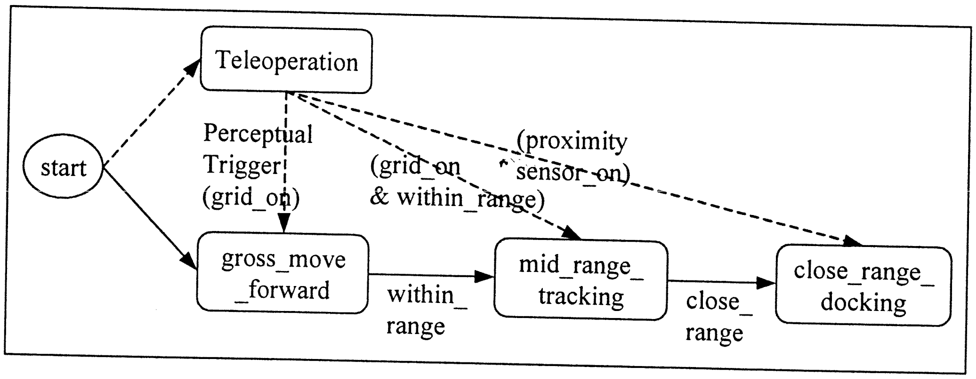


Figure 4. *Move_to_goal* motor behavior

Figure 5 illustrates the various motor behaviors constituting *Apply_tool* motor behavior, which performs the action of actually applying tools on workpieces. As can be seen, the tooling behavior requires moving the tool along a specified tool path (*move_along_path*), while maintaining tool angle and depth (*maintain_attitude*). The motion trajectory is further modified to avoid obstacles or exceeding the joint limits.

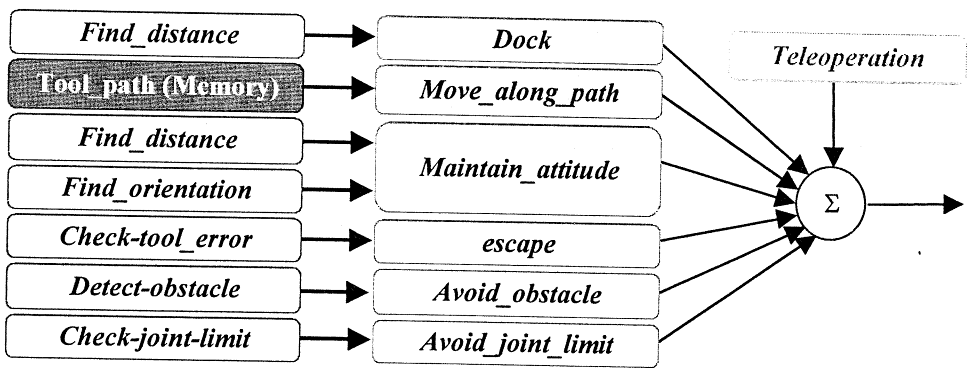


Figure 5. *Apply_tool* motor behavior

3. PERCEPTUAL BASIS

To provide the environmental information to the motor agents, sensory system is configured in a form compatible to the reactive agent based robotic architecture. This perceptual basis consists of a sensory module and perceptual software agents, as shown in Figure 6.

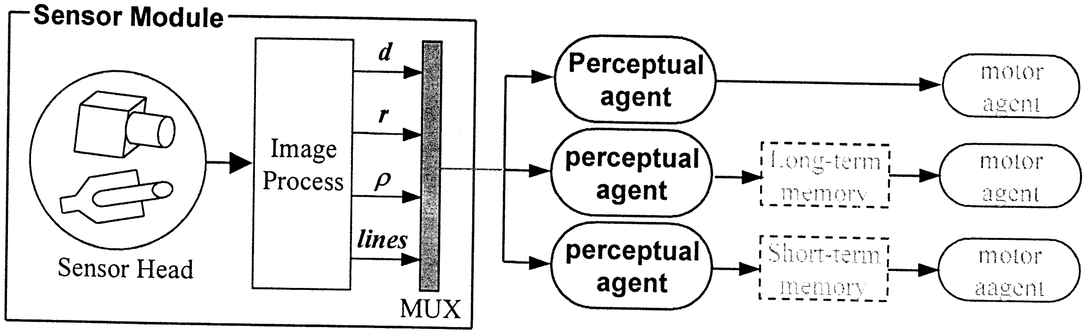


Figure 6. Perceptual basis

In the development of behavior-based robotic system, perception is viewed as a partner process with action. The need of motor control provides context for perceptual processing, whereas perceptual processing is simplified through the constraints of motor action. To take this interplay into account, perceptual agents conduct perception on a need-to-know basis: individual perceptual agent provides the information immediately needed by the motor agent which decides an action, not representations of the environment. The inherent parallelism and more targeted processing of behavior based robotics permits much more efficient sensor processing. In this process, perceptual agents may adopt compound sensing strategies, such as sensor fission, fusion and fashion. Furthermore since perception is a process deeply intertwined with the motor action, some active perception incorporates motor agent as an integral part. These processes are implemented in our perceptual mechanisms, and described in the following sections.

3.1. Structured light system

In our implementation, the sensor system is constructed based on a structured-light system, which is commonly used in industrial robotics for capturing part geometry. As shown in Figure 7, it consists of a laser beam projector that projects a beam pattern and a camera mounted at a slight tilt angle. A short-range infrared range sensor is also added to the module to provide near range data when precise motion path needs to be generated. The beam pattern projected over an environmental object provides visual reference to both motor agents and the human operator. Also, the laser beam projection may guide where to focus attention in the visual search process, resulting in significant reduction in the

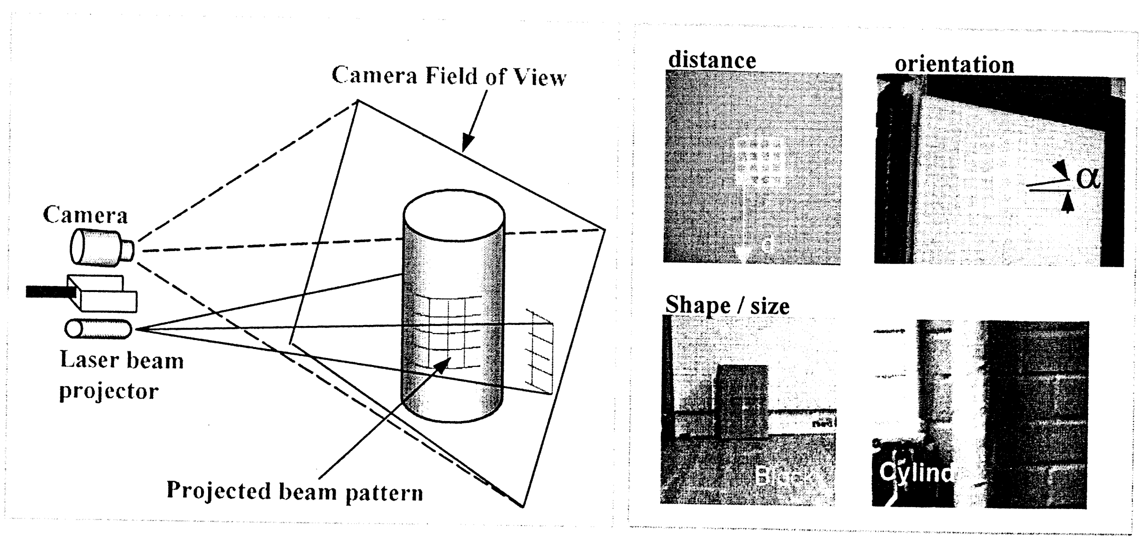


Figure 7. Structured light system

computational complexity. It has been shown that bottom-up visual search where matching is entirely data driven is NP-complete, whereas task-directed visual search has linear-time complexity. By analyzing the distortions in the projected grid patterns, the location, orientation, and surface details of a part can be determined, as illustrated in the right side of the figure.

To facilitate geometric interpretation of the beam pattern, image processing routines are implemented as an integral part of the sensor module. As illustrated in Figure 8, image processing involves image enhancement, curve fitting and geometric interpretation. Since many of the image processing routines are computationally extensive, a separate computer is assigned for it.

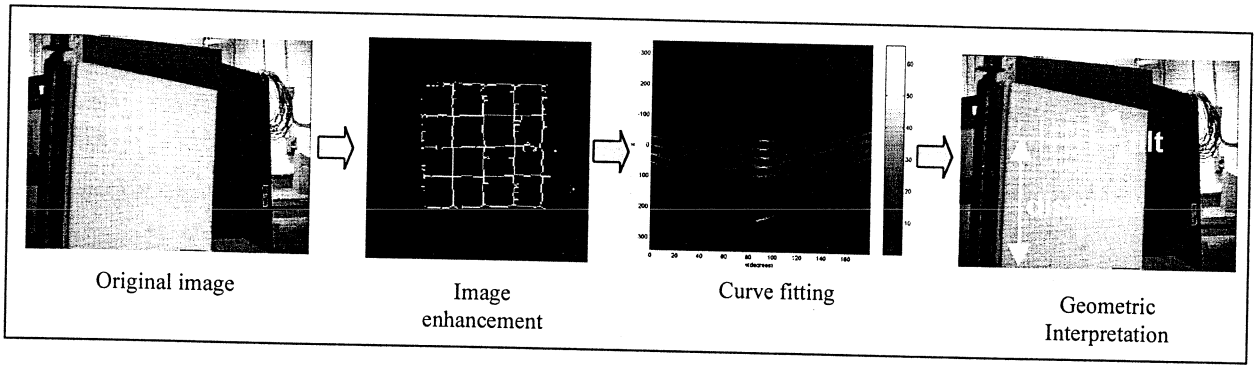


Figure 8. Image processing

3.2. Sensor sequencing in *move_to_goal* behavior

Due to the sequential nature of *move_to_goal* behavior, as shown Figure 9, its perceptual agent adopts 'sequencing' as the primary perceptual mechanism. The perception is accomplished by sequening the following perceptual behaviors.

find_goal_direction: From the center position of the projected landmark pattern in the camera field of view, it determines the direction from the current end-effector to the grid location.

find_goal_geometry: By analyzing the position and the distortion of the grid pattern, it determines the relative location and surface orientation of the workpiece.

find_close_range: Determines the close range distance and the surface orientation of the workpiece form the readings of the proximity sensors.

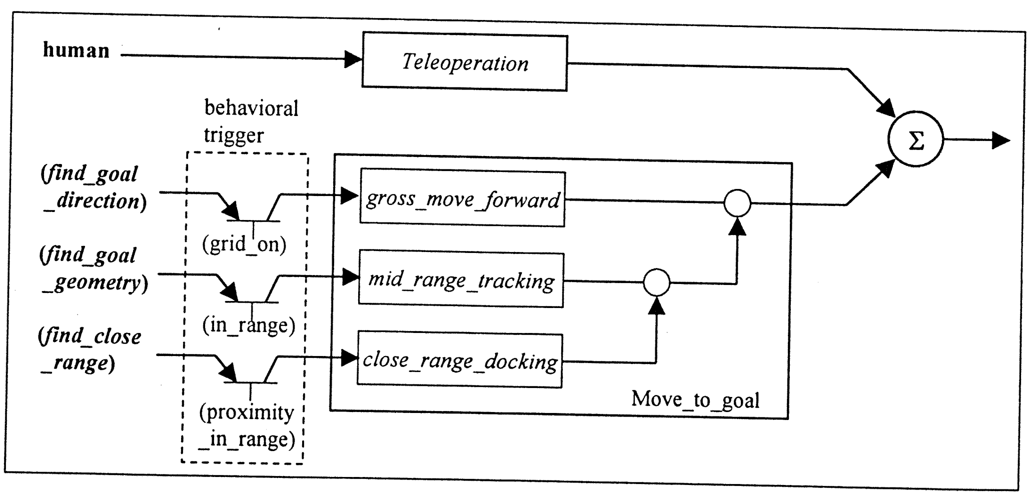


Figure 9. Perceptual sequencing in *move_to_goal* behavior

The above perceptual behaviors, triggered by certain sensory conditions, supply perceptual information to the corresponding motor behaviors. The sequencing of multiple behaviors is accomplished by subsumption, which is designated as the circular junctions in the figure. In the subsumption mechanism, one behavior subsumes the other behavior. Thus, for instance, *mid_range_tracking* behavior subsumes *gross_move_forward* behavior when both behaviors take effect.

3.3. Active perception in *inspection* behavior

Reactive robots are built on spontaneous reaction to the current sensory inputs. However, if the environment is less dynamic and there is useful information that is accurate, durable and reliable, then it can be worthwhile in providing more persistent representations environmental knowledge that encodes this information to the robot. The motor behavior, *apply_tool*, performs the actual operation of applying a tool onto the work piece. As can be seen in Figure 4, among its many constituent motor agents, *move_along_path* moves the end-effector along a prespecified tool path. Rather than accepting instantaneous environmental perception, the *move_along_path* acts on motion reference provided by a predefined tool path. Since a tool path needs to be fitted with complex geometric shape and defined with reasonably high spatial resolution, the perceptual agent, *define_tool_path*, is designed as a relatively complex process involves motor action as an integral part. As illustrated in Figure 10, the perception involves the following processes: 1) the sensor head is first moved to and patterned beam is projected onto the target workpiece, 2) the shape of the projected beam pattern is analyzed to estimate the shape and size of the workpiece, and 3) the sensor head is revolved around the workpiece, the projected beam patterns are analyzed and collected to from a tool path. Rather than continually regenerating the tool path at every control instance, the sensing routine is conducted less frequently and the resulting path is stored in a long-term memory. This path data is referenced throughout the action of *apply_tool* behavior.

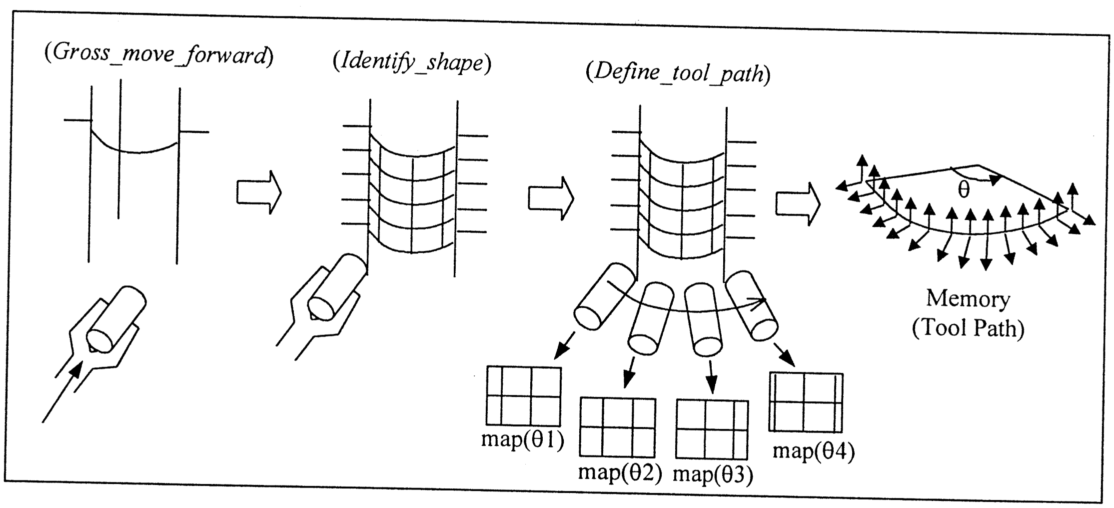


Figure 10. Active perception for inspection behavior

4. EXPERIMENTAL DEMONSTRATION

To demonstrate technical feasibility of the proposed perceptual basis, experimental operations are performed using a small mobile manipulator kit. As shown in Figure 11, it consists of a 4 d.o.f manipulator mounted on a mobile platform. Mounted on the hand of the manipulator are small pin-hole camera and a laser diode projecting 4x4 square gird beam pattern. Another camera is placed on a pan-tilt mount in such a way that looks over the task site, and another laser diode is mounted that projects a crosshair beam pattern.

4.1. Demonstration of perception in *move_to_goal* behavior

An experimental operation was performed to demonstrate the action of *move_to_goal* behavior. Figure 11 shows the world view captured by the robot's hand camera throughout the behavioral action of aligning robot hand onto a cylindrical object. At first, the projection of crosshair beam initiates the *gross_move_forward* behavior, and the corresponding perceptual agent, *find_goal_direction*, deduces motion references in three directions from the relative

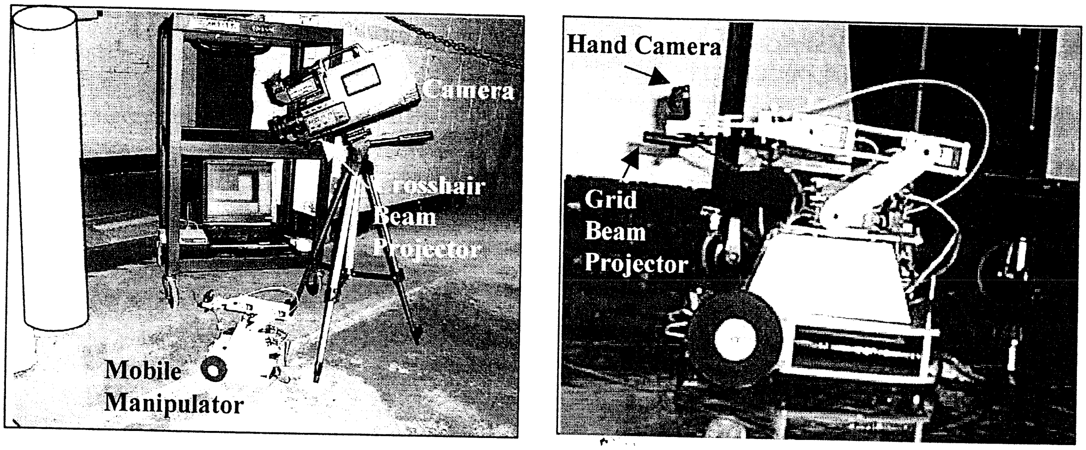
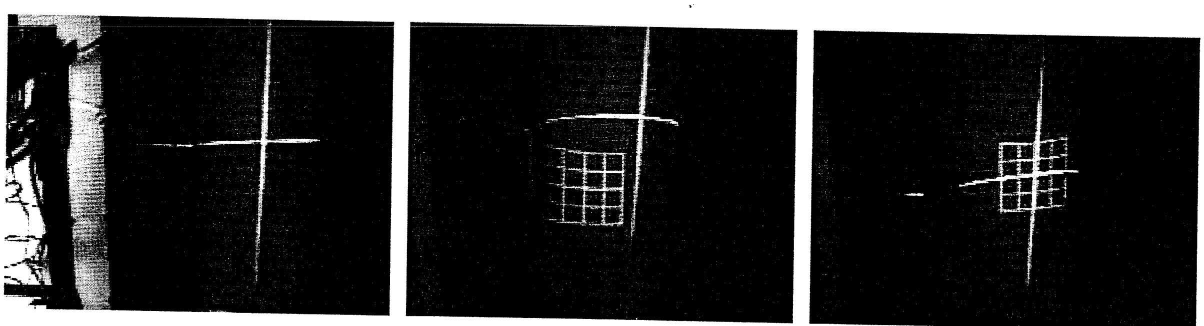


Figure 11. Experimental setup with mobile manipulator kit

location of camera's view center and the center of the crosshair. As the robot gets closer to the target object, the grid beam is projected to identify the orientation of the part surface, and *mid_range_tracking* behavior is initiated. After the robot hand is positioned with the landmark at correct orientation, *close_range_docking* takes effect until the hand touches the workpiece. The results show that the perceptual agents can effectively support the motor behavior in



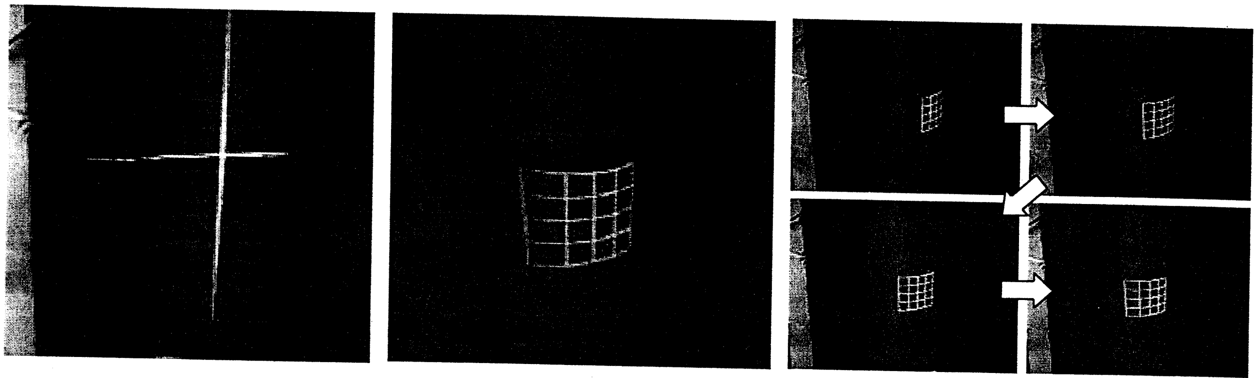
a) *Gross_move_forward* b) *Mid_range_tracking* C) Prior to *Close_range_docking*

Figure 12. Perceptual actions in *move_to_goal* behavior

semiautomatic tool alignment tasks.

4.2. Demonstration of perception in *inspection* behavior

Another experimental operation was performed to demonstrate an active perception process in *inspection* behavior. As shown in Figure 13, *inspection* adopts two step process. After the robot is moved to the vicinity of the workpiece, the grid beam is projected at a distance to identify the shape of the object. Subsequently, using the shape information as motion reference, a perceptual agent, *define_tool_path*, is initiated to generate the tool path. *Define_tool_path* is a unique example of active perception process which incorporates motor action to aid the perception. To generate a tool path covering a large area with relatively fine resolution, the grid beam is moved bay the robot to scan across the diameter of the workpiece, while the coordinates of the grid points are recorded in a tool trajectory. In this process, the manipulation is fully automated in order to provide accurate and even scanning motion.



a) *Gross_move_forward* b) *Identify_shape* c) *Define_tool_path*

Figure 13. Perceptual actions in *Inspection* behavior

5. SUMMARY AND CONCLUSION

To support reactive teleoperation, it is proposed to establish perceptual basis based on structured light system. To further enhance teleoperation in partially structured environment, perceptual behaviors are developed to support more complex motor behaviors that facilitates semi-autonomous operation. In particular, perceptual agents are developed that use complex sensing process: sensor fashion and active sensing. Combined with the projection of structured light, it was possible to provide simple and effective perceptual agents dedicated to complex motor behaviors. The devised perceptual paradigms are expected to serve as important building blocks in composing sensory basis for semi-autonomous teleoperation, which require compound motor behaviors.

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