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Real-Time Collision Avoidance in Teleoperated Whole-Sensitive Robot Arm Manipulators

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Real-Time Collision Avoidance in Teleoperated Whole-Sensitive Robot Arm Manipulators

Vladimir J. Lumelsky, *Senior Member, IEEE*, and Edward Cheung

Abstract— **In traditional teleoperation systems, the human operator is saddled with two distinct tasks: 1) moving the robot arm to its desired position, and 2) avoiding obstacles that can obstruct the arm motion. The current robot teleoperation research concentrates on providing the operator with as much input information about the task site as possible using, for example, stereo vision or contact force feedback. These methods presume that the operator is capable of planning motion for the entire body of the robot in a cluttered environment. Studies show, however, that the operators, first, cannot address both tasks in real time, and second, are not good at generating collision-free motion in a complex environment. Recent results in sensor-based motion planning suggest that the collision avoidance task can be handled automatically, thus freeing the operator for global control. To this end, it is also proposed to use whole-sensitive arm manipulators whose whole bodies are covered with a sensitive skin sensor to detect nearby objects. The data from the skin is processed by motion planning algorithms, to avoid collisions for the entire arm body in an unknown or time-varying environment. The motion of the operator-controlled master arm is either repeated faithfully by the slave arm, or, to avoid collisions, is used as general guidance. In the latter case the slave arm attempts to be as close as possible to the positions commanded by the operator, without jeopardizing its safety. The result is an efficient, safe and robust hybrid system in which integration of control by the operator and the automatic system is done transparently and in real time.**

I. Introduction

In THIS PAPER, we address the problem of generating collision-free motion in an operator-assisted teleoperated robot arm manipulator system. We concentrate on the following important requirements to the system: 1) a "real" real-time operation—for example, the operator cannot afford to stop motion in order to consult with a model or to study the supervising camera views; 2) a guarantee of collision-free motion for the entire body of the arm manipulator; 3) an ability to handle obstacles of arbitrary shapes. To our knowledge, none of these requirements are satisfied in today's systems. Furthermore, achieving such characteristics presents a major bottleneck in the current theoretical and engineering work on intelligent man-assisted autonomous robotic systems. Removing those bottlenecks is the main motivation behind this work. The suggested methodology draws on recent work on motion planning with incomplete information for whole-sensitive robots [1], [2].

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There has been much work in recent years in the area of teleoperation and telerobotics. In these systems, the robot arm is commanded to move in real time by a human operator who is viewing the progress of the operation. Usually, the decisions on both the task of moving the arm to the desired position and the task of avoiding obstacles that obstruct the arm are made by the human operator. A large branch of research in this field has concentrated on aiding this process by providing the operator with as much information about the scene as possible in the form of visual and/or force feedback. More recently, this research has moved toward telepresence, where the operator is made to "feel" that he is located at the task site [3]–[5]. One unavoidable side effect of these approaches is that the operator is flooded with vast amounts of information that he may not be able to process in real time.

An additional information processing problem relates to the sensing media used. For example, a challenge of using vision in a cluttered environment is that the robot arm may itself occlude the view to an impending collision. This problem has been addressed by using several cameras spread around the task site, which demands from the operator an ability to simultaneously monitor the various video inputs during the operation. In addition to the problem of occlusion, in some remote teleoperation systems there may be a significant time delay between the specification of a command and its execution. An example of this case is a robot in earth orbit controlled from the ground. Due to the time delay caused by the distance separating the robot and control site, the operator may not be able to give the appropriate commands to avoid an approaching object even when the entire scene is clearly in view.

To help overcome the problems of occlusion and time delay, researchers have used CAD based models and computer graphics overlays of the camera views to verify that the path of the manipulator is collision-free [6]. This obviously precludes a real-time operation. Perhaps more importantly, such techniques are not practical for guaranteeing collision-free motion for the entire body of the robot arm manipulator. The robot arm can still be given commands that cause it to collide with objects—for example, because of the changes in the environment or inadequacies of the model. Moreover, these approaches presume that human geometric reasoning is adequate for the task. Studies of human performance in motion planning suggest, however, that humans have inherent difficulty with planning collision-free motion of the entire body of even a simple two-link planar robot arm [7], even if the entire scene is clearly comprehensible and visible. These

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results indicate that further assistance to the operator is needed to protect the robot arm and the objects in its environment from collisions, as any mishap may lead to undesirable down time of the equipment or human injury.

We propose here a hybrid teleoperation system where the operator carries out general control and indicates intermediate goals and desired motion, whereas the task of collision avoidance is shifted to an automatic sensor-based subsystem. This is accomplished via a whole-sensitive robot arm manipulator—that is by the addition of a sensitive skin covering the robot arm body, and the appropriate data processing algorithms for motion planning and obstacle avoidance. Such a system has been built and tested in our robotics laboratory. Our sensitive skin happens to be based on infrared proximity sensors, although many other types or combinations of types of sensors could be used to fit specific applications. Using a suitable input device, such as a joystick or master arm, motion commands can be passed directly from the human operator to the *slave* robot arm—thus the operator guides the robot arm manipulator as in any conventional system. However, if obstacles are obstructing the arm, its motion is modified in real time by the automatic motion planner so as to maneuver the arm around the obstacles to prevent collision.

The motion planning function in the teleoperation system is largely based on recent results in sensor-based robot motion planning [2], [8]. The transition from the operator to computer control for obstacle avoidance is both smooth and transparent to the operator, i.e., he need not pause for any explicit shift in control. Using the sensitive skin, together with the accompanying sensor data processing and motion planning algorithms, collision-free motion for the entire robot arm manipulator body is achieved, even in an unknown or time-varying environment.

We foresee that application of whole-sensitive robots will increase systems flexibility and safety, and soften space requirements on generating complex motion in a variety of tasks. This will affect more conventional single-arm or multiarm systems on the factory floor and in construction industry, as well as more specialized systems such as in outer space. In a recent study presented to the U.S. Congress [9], it was shown that the estimated time required for space walking astronauts performing extra vehicular activity (EVA) to maintain the Space Station Freedom far exceeds the amount of time currently planned or feasible. One conclusion from this is to reduce the amount of EVA by shifting a large number of maintenance tasks to teleoperated robots. It is estimated that the time required to accomplish certain tasks with telerobots can be reduced to one third by using obstacle avoidance techniques. The approach presented here directly addresses this issue and can be seen as complementary to the current development work on similar technology within the projects of Space Shuttle Orbiter and payload processing at the Kennedy Space Center [10], and the U.S. Department of Energy's Waste Management Project [11].

The following material is organized as follows. In Section II, the major components of the teleoperated motion planning system are presented: the sensitive skin sensor, the sensor data processing algorithm called the Step Planner, the Mini-Master Arm that serves as the input command device, and the overall motion planning algorithm that guides the operation of the slave arm as it navigates in its environment. Then, a simulated example that illustrates the system operation is presented in Section III, followed by a discussion of the experimental work with the developed system in Section IV. Section V summarizes the results presented.

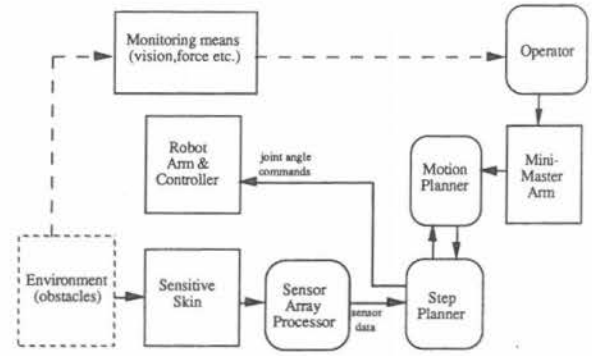


Fig. 1. Information flow diagram of the robot teleoperation system.

II. Components of the Motion Planning System

The general information flow diagram of the robot teleoperation system, depicted in Fig. 1, shows the interaction and hierarchy of the various units in the system; in the diagram, the decision making (by software and by human) and hardware items are shown by rectangles with the rounded and square corners, respectively. The sensitive skin covers the robot arm, and detects nearby obstacles in the environment. The next incremental move within the regular sample rate of the robot arm is based on the current sensor data and the desired motion command from the Motion Planner; to allow that, the Sensor Array Processor and the Step Planner together process the data from the hundreds of individual proximity sensors covering the sensitive skin. The Motion Planner guides the overall motion of the arm and decides when and where the arm should move in free space, or slide along the surface of obstacles. The Mini-Master Arm is the operator's Input device in this master–slave telerobot system; a General Electric P5 industrial manipulator serves as the slave arm.

The details of computer processing of the automatic motion planning part of the system can be found in [2]. The computational load added due to the teleoperation part is negligible—it has been accommodated with the same computer hardware. In brief, all the necessary computations are done in parallel and in real time, based primarily on the transputer technology. Call a *system cycle* the time period within which the system has to do the following: collect information from the operator and from all sensors (about 500 of them in our prototype); do the calculations necessary to decide on the size and direction of the next step so as to guarantee no collisions within and at the end of the step; and send the corresponding commands to the motors controlling the arm joints motion in order to execute the step. The length of the cycle is dictated by the control system of the robot manipulator at hand. Our General Electric arm is quite typical in this respect: its sampling rate is about

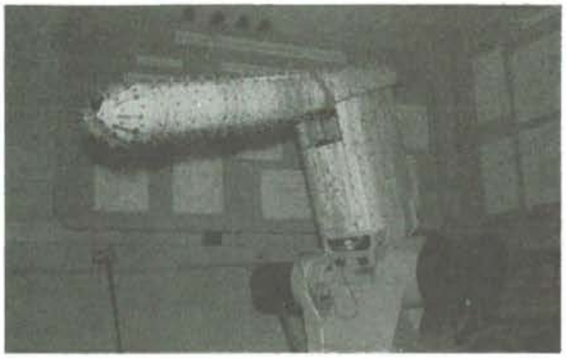


Fig. 2. Photograph of the robot arm with the sensitive skin.

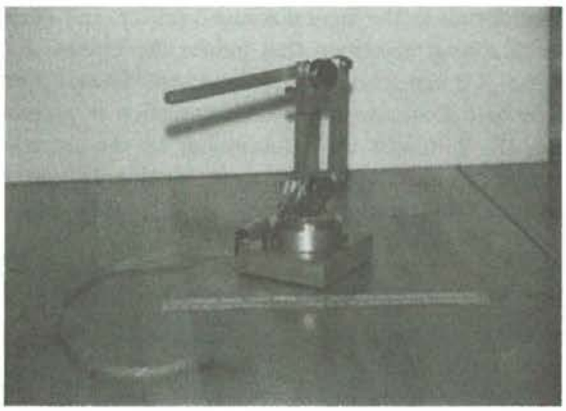


Fig. 3. Photograph of the Mini-Master Arm.

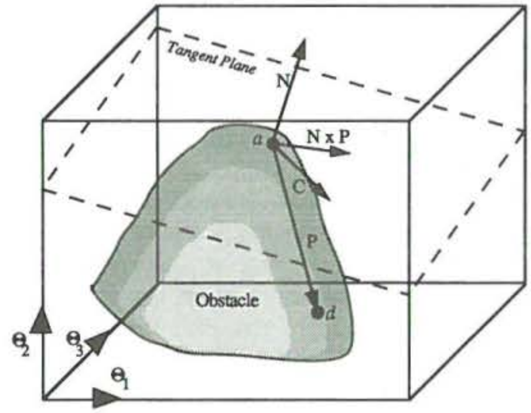


Fig. 4. Motion of the automaton on the tangent plane at the contact point to the obstacle in the configuration space is along the vector $\boldsymbol{C}$, where $\boldsymbol{C} = (\boldsymbol{N} \times \boldsymbol{P}) \times \boldsymbol{N}$; $\boldsymbol{N}$ is the normal of the tangent plane; $\boldsymbol{P}$ is the vector from a (the current position of the automaton) to d (the desired position).

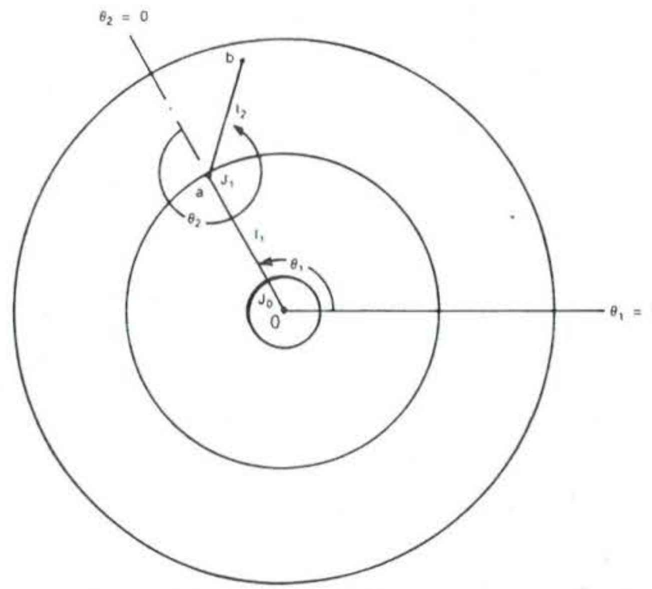


Fig. 5. Arm model for the motion planning example. l_1, l_2—links; J_0, J_1—joints; q_1, q_2—joint values; b—arm endpoint. The three circles indicate the reach envelopes of both links.

20 samples per second, which makes the cycle time roughly 50 ms. This sampling/processing cycle has been satisfied rather easily in the system. In future systems, if, for example, much larger sensor arrays or/and shorter sampling cycles are needed for faster motion or increased accuracy, further parallelism can easily be achieved by adding more computing units.

Given this independence of the sampling rate from the motion planning question, the speed of the teleoperated arm motion is limited mainly by that allowed by the robot control system. This limit is not likely to be reached because the operator, who dictates the actual speed by moving the Mini-Master Arm, tends to take more time to figure out the desired motion, especially in a cluttered environment. Due to the implementation of the control system of our manipulator, the arm speed has been kept within the range about 15 cm/s at the arm endpoint. Although the motion planning subsystem can in principle accommodate a significant increase in speed, other limitations—e.g., the sensitivity range of the skin—may play a role. Each of the major components in the system is discussed in more detail below.

A. Sensitive Skin Sensor

The individual active optical proximity sensors that cover the skin are organized in the form of a grid on the surface of the arm; see Fig. 2. The skin covers all the areas of the arm that might come in contact with obstacles. This includes practically the whole arm body, including the endpoint and joints. No physical contact with objects in the environment takes place during the telerobotic operation, as sensors use the reflected light to sense obstacles.

To increase immunity to ambient light and to allow operation on multiple frequencies, the light emitted by a sensor is amplitude modulated. If reflected back by an obstacle, it is synchronously detected by the receiver section of the sensor. The output of the sensor is an analog signal proportional to the amount of light reflected off the obstacle. By using two frequencies and parallelizing the polling of the arm, the total time necessary to read all the sensors is reduced. Each sensor is polled seventeen times a second by the Sensor Array Processor; see Fig. 1. In the current implementation, 475 sensors blanket the robot arm and the sensing distance of each sensor is up to 15 cm. The motion planning system operates the arm major linkage which combines the first three arm joints and is responsible for bringing the wrist in the desired location in the workspace. The remaining wrist joints are not controlled directly, although the collision-free motion of the wrist is still guaranteed.

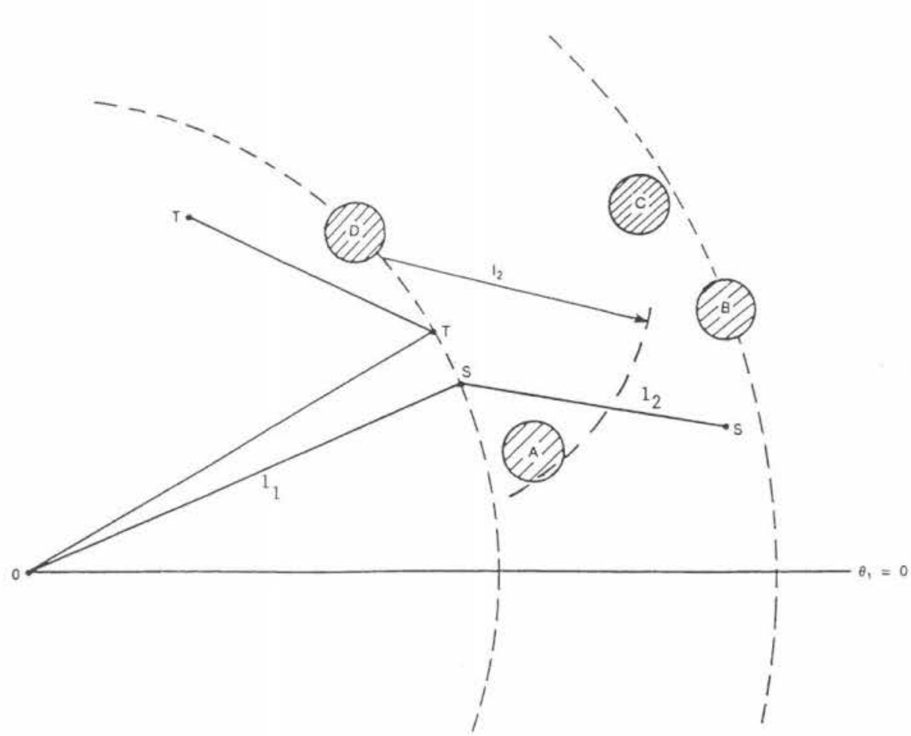


Fig. 6. Four simple obstacles, A, B, C, and D, interfere with the arm motion. The arm is requested to move from the position S to the position T. When link l_1 touches obstacle D, obstacles A and C are in the way of link l_2.

The skin proper presents a Dacron-Epoxy-based flexible circuit board that has been processed using standard circuit board development techniques; the board is then fastened onto the surface of the robot arm. The circuit board provides both structural support and electrical interconnection for the optical components, and allows the accurate placement of several hundred sensor pairs (for more details, see [8]). The resulting system is quite robust in that it is insensitive to the variability in characteristics of individual sensors and requires no elaborate sensor selection and calibration procedures.

B. Step Planning Algorithm

The sensitive skin, the robot arm, and the software that control them present the lower level subsystem of the motion planning system. On the next level is the Step Planner (see Fig. 1), which is a module that plans incremental steps at every moment causing the arm to move in free space toward its target position or slide along obstacles. In the latter case, the Step Planning algorithm guarantees that, first, no collision with the obstacle takes place, and second, a contact with the obstacle is maintained at the end of the step. The term "contact" here refers to the situation when an obstacle is within the sensitivity range of one or more skin sensors. If the arm moves in free space so that no skin sensor detects an obstacle, the consecutive arm positions generated by the Step Planner move the arm directly to the selected target position, using any desired method of trajectory control methodology. This can be, for example, a straight-line motion of the arm end effector in the work space, or a straight line in the configuration space, or any other predetermined curve.

Once the skin sensors detect an obstacle(s), the Step Planner starts generating steps to safely maneuver the arm around the obstacle. These steps are taken along the tangent plane to the obstacle, which is found by the Step Planning procedure. To generate the local normal of the tangent plane at the point of contact with an obstacle, the Step Planner takes into account the location of the point of contact on the robot body; the system can handle simultaneous interaction with multiple obstacles [8].

Safe motion is guaranteed at every step of the arm. This is made possible by utilizing the sensing range of the sensitive skin: at every step, an envelope of certain thickness (the current range of the sensor) is certified to be free of obstacles. The next step is calculated such that after its completion, all points of the arm body are still inside the safe envelope. This process then repeats at each new position of the arm.

If more than one point of the arm body are simultaneously in contact with one or more obstacles, all such contacts are evaluated by generating a local tangent plane at each contact. Then, one local tangent plane is selected such as to guarantee safe motion. The selection is based on the general direction for sliding along obstacles, the conditions for leaving the obstacle, and the trajectory from the Motion Planning algorithm which directs the robot toward the desired target position (Fig. 1).

C. Mini-Master Arm

The Mini-Master, Fig. 3, is controlled by the operator and serves as the input device of the telerobotic system. It is a scaled kinematic duplicate of the P5 arm, and allows the operator to specify a desired position of the big slave manipulator. Since the first three joints of the slave arm are

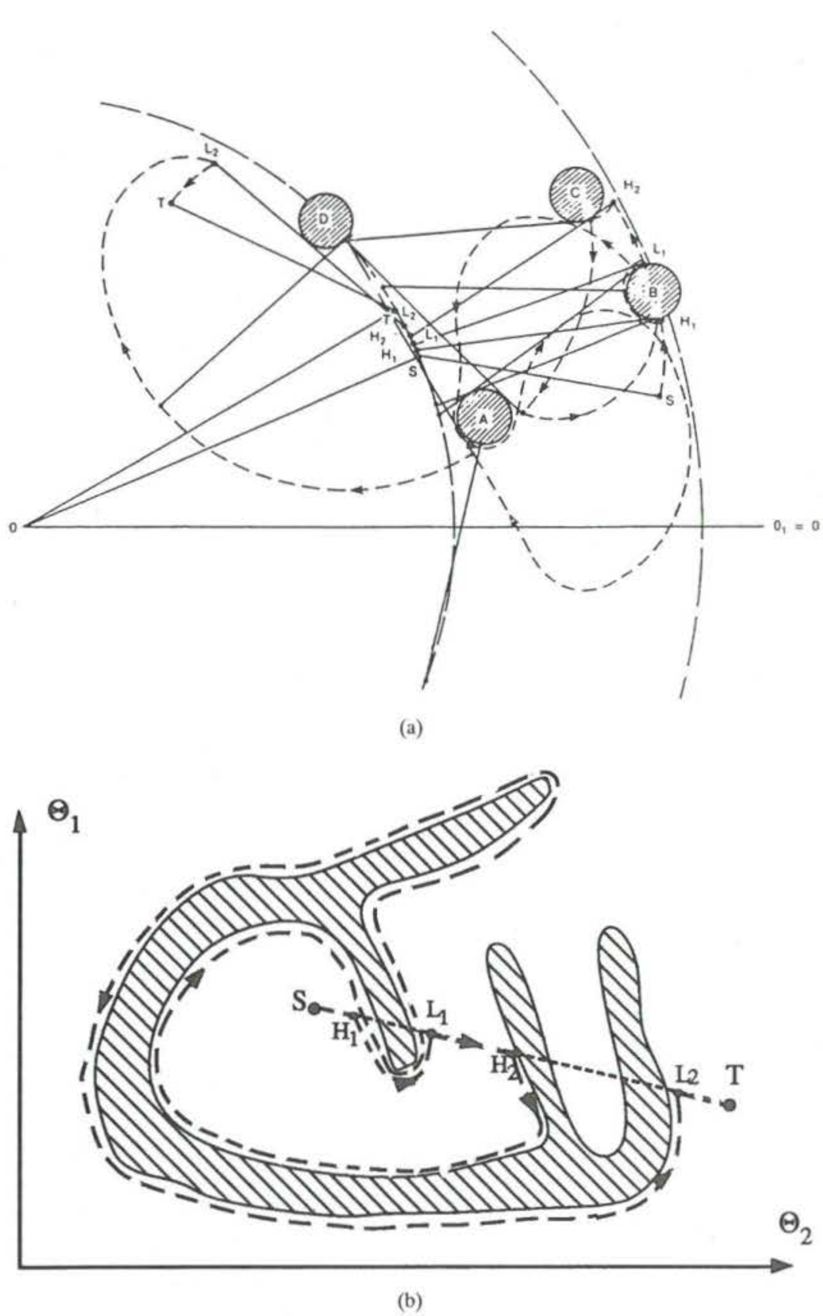


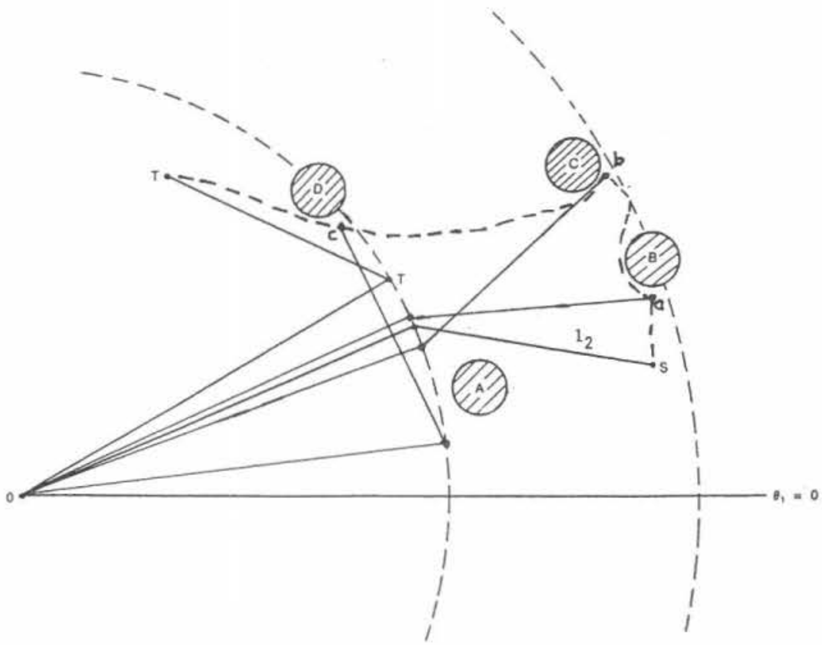
Fig. 7. Arm motion under the automatic motion planning algorithm [1] (the dashed line represents the path). (a) Work space presentation; also shown are some intermediate positions of link l_2. (b) Configuration space presentation of the path.

directly controlled by the motion planning system, the joint angles of the corresponding joints are measured on the Mini-Master using potentiometers. The joint angles are then passed on to the Motion Planning algorithm as the desired position for the slave arm. Currently, the signal from the potentiometers is somewhat noisy, which sometimes causes a shaking of the arm. This can be remedied by replacing the potentiometers by high resolution digital encoders.

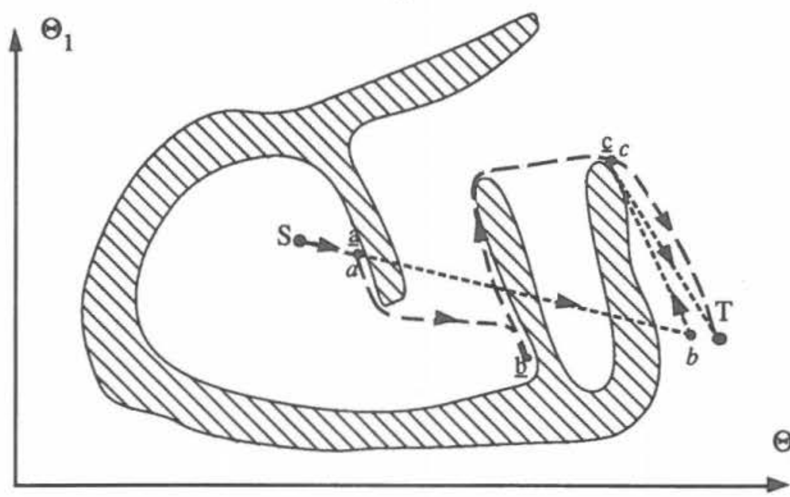
D. Teleoperation Motion Planning Algorithm

The Motion Planning algorithm transforms the preprocessed sensor data and commands from the Mini-Master into global planning decisions that guide the arm overall motion. The Motion Planner commands the arm to move in free space toward the desired position, or if an obstacle is encountered, causes the arm to maneuver around it. In the latter case, the arm is commanded to slide along the obstacles surface without making contact. This sliding can be accomplished in a number of ways; the one used in our implementation is to slide so as to locally minimize the difference between the actual position of the arm and the one requested by the operator, as explained below.

Moving the slave arm by commanding its three joint angle positions is equivalent to moving a point automaton in the three dimensional space, called the configuration space, whose axes correspond to the degrees of freedom of the arm. Real obstacles in the workspace of the slave robot arm produce corresponding images in the configuration space in the form



(a)

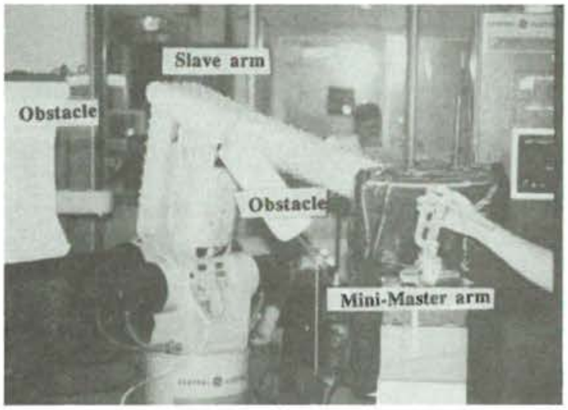


(b)

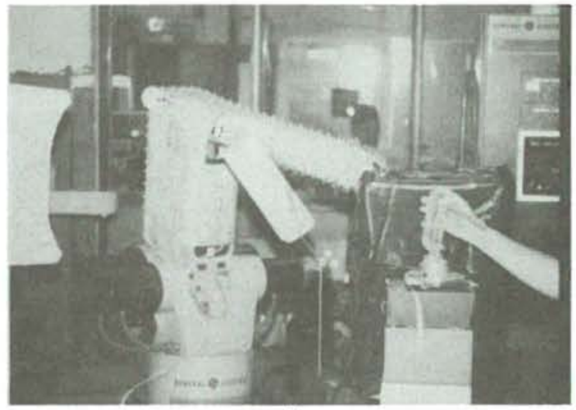
Fig. 8. Performance of the teleoperated system in the example of Fig. 6. (a) Work space presentation of the slave arm path (dashed line). (b) Configuration space presentation. The paths of the slave and master arms are shown in dashed and dotted lines, respectively. Named points along the paths of the slave and master arm are shown as underlined and italicized respectively. First, the operator, hoping for the better, simply moves the master arm toward position b. Unfortunately, the slave arm responds by moving to $\underline{b}$ and stopping there. The operator then corrects the path by moving first to c and then to T, which causes the slave arm to produce path segments $\underline{bc}$ and $\underline{c}$T.

of forbidden locations for the point automaton. Despite the fact that the images of the obstacles are completely unknown to the motion planning system, the automaton may slide along the obstacle images when the arm is obstructed by an obstacle. This is done by moving the automaton, using the Step Planning algorithm [2], along the tangent plane at the contact point in the configuration space.

Depending on whether or not an obstacle is obstructing the slave arm, the system is controlled in one of two modes. Mode 1 takes place if the path to the desired position is not obstructed by an obstacle. In this mode, the automaton moves in a straight line in the configuration space to the desired position. If, however, an obstacle appears obstructing the path to the desired position, the arm enters Mode 2 where the automaton slides without contact along the surface of the obstacle, such as to locally minimize the Euclidean distance between the desired and actual positions. An example of Mode 2 motion is shown in Fig. 4; points a and d are the current and the desired (at the end of the step) positions of the automaton respectively. In this case, the automaton is obstructed by the obstacle and slides along the vector $\boldsymbol{C} = (\boldsymbol{N} \times \boldsymbol{P}) \times \boldsymbol{N}$, where $\boldsymbol{N}$ is the normal of the tangent plane and $\boldsymbol{P}$ is the vector connecting points a and d. At every step along the surface of the obstacle, new vectors $\boldsymbol{N}$, $\boldsymbol{P}$, and $\boldsymbol{C}$ are calculated in order to cause the automaton to slide along the obstacle. This sliding continues until the vectors $\boldsymbol{N}$ and $\boldsymbol{P}$ are colinear, or



(a)



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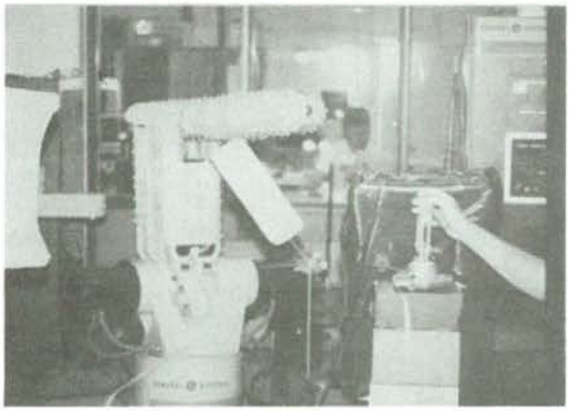

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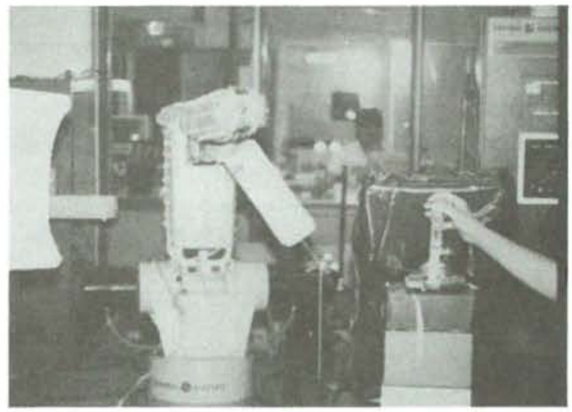

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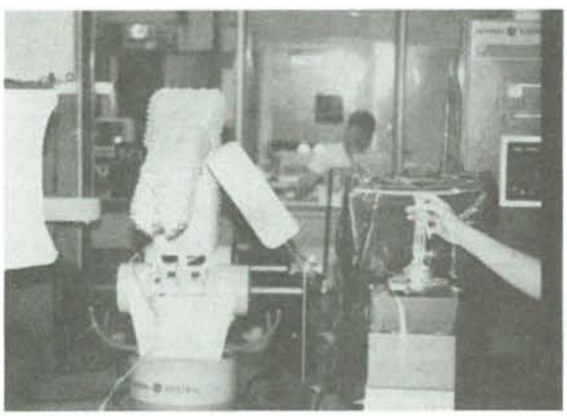

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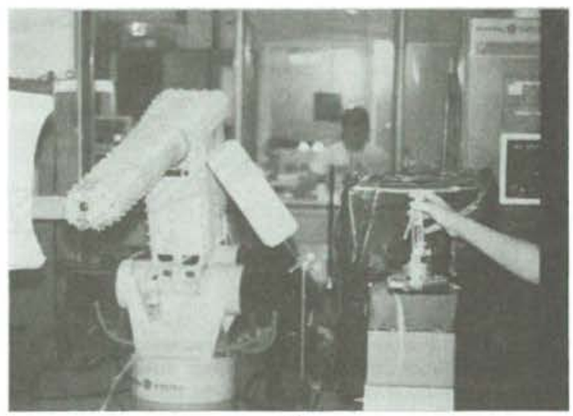
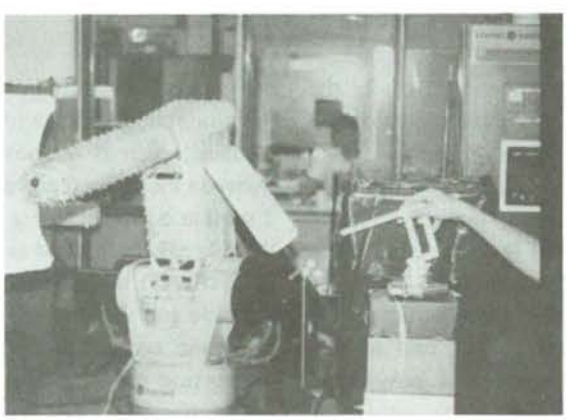


(f)



(g)

Fig. 9. Experiment 1. Motion in a scene with two unknown still obstacles.

when the Euclidean distance between points a and d can no longer be locally minimized.

We emphasize that the only conflict between the operator commands and the automatic planning system that can ever take place is if the operator guides the arm to an outright collision. The command given to the slave arm in this case is based on both the data from the sensitive skin and the operator commands, and makes the robot "slide" along the obstacle. This will result in the closest possible position to the one requested by the operator. If, on the other hand, the operator's commands do not conflict with the arm safety, they are executed precisely as requested. The positions dictated in real time by the operator can be in close proximity to the current position, or they can be far from it, in which case the intermediate motion would involve a number of steps.

No constraints are imposed on the operator in how fast or how far he moves the Master Arm. The operator needs not pause or push a special button in order to avoid the obstacle. The switch between Mode 1 and Mode 2 is automatic, transparent, and smooth, allowing the robot arm to execute safe motion continuously at all times. The task of avoiding obstacles has been completely off-loaded from the operator, allowing him to better concentrate on global planning of the task at hand.

A concern that can be heard sometimes is that the correction of the motion via automatic sensor-based planning may be too "simplistic" and not fit into the operator's higher-level plans. This thinking calls for a hierarchical control in which the automatic system would be monitored and could be overridden by the operator. While such a system is fully feasible within the framework presented, its wisdom is questionable: it assumes that the operator is in general better in taking care of the arm safety. The experience with the system described (see also [7]) suggests, though, that in cases when the whole or a large part of the robot body is subject to collision the operator has serious difficulties in reasoning about collision-free motion. Thus, leaving this task to an automatic planning system may be the only choice.

III. Illustrative Example

To illustrate the operation of the developed teleoperation motion planning system, we compare its performance to that of an existing two-dimensional automatic motion planning algorithm [1] using a contrived example. The planar two-degree of freedom robot arm used in this example is shown in Fig. 5. The arm consists of two links, l_1 and l_2, and of two revolute joints, J_0 and J_1; joint J_0 is fixed. Although the shape of the arm links and the obstacles (e.g., their convexity or concavity) is of no importance to either the automatic or the teleoperation system, for the sake of simplicity the shapes of the links and obstacles are shown as simple straight line segments and circles, respectively.

The placement of the obstacles is shown in Fig. 6. The robot arm is required to move from the starting position S to the target position T. Fig. 7 shows the path generated by the automatic motion planning algorithm [1]. The algorithm has no previous knowledge about the obstacles, and uses local sensory data only. As one can see, under automatic motion planning algorithm the arm travels the section H_1 to L_1 twice, and requires the arm to take the longer path along the exterior perimeter of the configuration space obstacle to reach L_2.

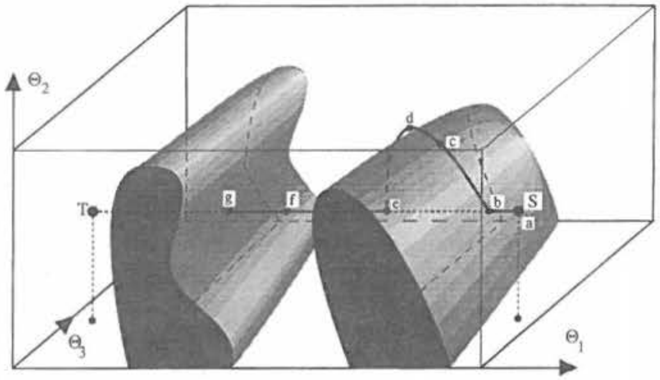


Fig. 10. Sketch of the configuration space of the robot arm in Experiment 1. The letters $a, b, \cdots, g$ refer to the position of the slave arm in the corresponding photographs in Fig. 11.

The action of the teleoperation motion planning system is shown in Fig. 8. First, the human operator moves the Mini-Master arm from S toward T (the path of the master and slave arm is shown in the dotted and dashed lines, respectively). The slave arm follows the Mini-Master using Mode 1 until point a (same as $\underline{a}$), whereupon the slave arm encounters an obstacle. At this point the slave arm enters Mode 2 and slides along the obstacle to prevent collision. The Mini-Master continues to move to point b; while attempting to follow, the slave slides along the obstacle until point $\underline{b}$, where it stops. The operator, realizing that an impasse has occurred, decides that a less simpleminded solution with an intermediate position is necessary, and moves the Mini-Master to point c. The slave arm then resumes motion toward the Mini-Master, and moves to point $\underline{c}$. The operator then finishes the motion by moving the Mini-Master to T. The slave arm is able to follow and arrives safely at T. Note that the generated path in this instance is shorter than the one produced by the automatic algorithm in Fig. 7. Performance is improved because the planning system is able to combine local sensor data with global information (commands) provided by the human operator.

IV. Experimental Validation

In a typical experiment, several objects of planar and curvilinear shape unknown to the motion planning system are placed in the reach envelope of the slave robot arm. The operator guides the arm using the Mini-Master Arm, while paying no particular attention to the location or placement of obstacles, and not trying to make sure that all parts of the arm body are collision-free. In other experiments, the operator does not even try to give a trajectory of the motion—instead, he places the Mini-Master Arm in some intermediate position, and when the slave arm is close enough to it, he moves the Master Arm to some other intermediate goal on the way to the desired target position. In all such cases the slave arm would move smoothly among obstacles trying to reach the positions indicated by the Master Arm. No collisions with obstacles ever took place.

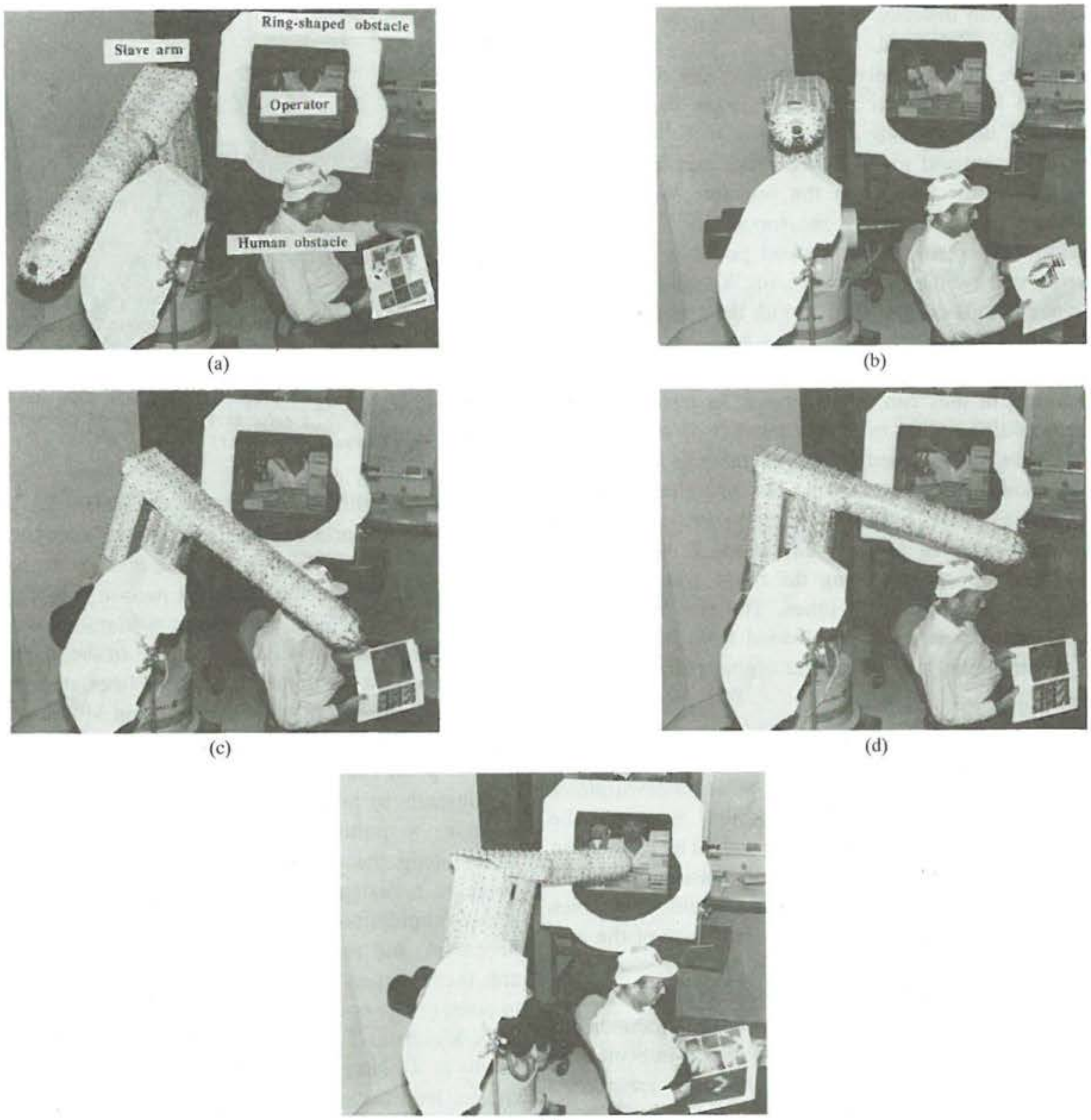


Fig. 11. Experiment 2. Here, the operator's view of the task area is blocked by an object, and a human has entered the robot work space.

A. Experiment 1

To simplify the experiment, only one axis of the Mini-Master has been moved during this experiment, the other axes were left unchanged. Two unknown obstacles are placed in the reach envelope of the slave arm (see Fig. 9(a)); the corresponding configuration space presentation is given in Fig. 10. In Fig. 9(a) the motion of the slave arm is unobstructed, and so it faithfully replicates the commands given by the Mini-Master Arm. The rightmost object is encountered first; Fig. 9(b) (point b in Fig. 10). Due to the object's shape, the slave arm is able to slide over it (Fig. 9(c) and (d)) while locally minimizing the distance in the configuration space between the desired and actual position of the slave arm. The sliding continues until the position shown in Fig. 9(e) is reached, where the slave arm reaches again the position commanded by the Mini-Master Arm. The slave arm then moves as commanded by the Mini-Master until the left most object is encountered (Fig. 9(g)). Because of the object's shape, the arm does not move further as the distance between the desired and actual positions of the slave arm can no longer be locally decreased, "refuses" to collide with the obstacle and halts at some distance from the surface of the obstacle.

B. Experiment 2

Here, the operator's task has been made more complicated compared to Experiment 1. He is physically further removed from the slave arm; his view of the slave robot arm has been blocked by an obstacle (a ring-shaped obstacle, Fig. 11(a)), and so he cannot directly observe many of the potential collisions. In addition, a human has entered the work space of the robot arm; he pays no attention to the arm motion and creates a moving obstacle in the course of the experiment.

The operator's task is, again, to guide the slave robot arm around its environment from its starting position, Fig. 11(a), to the target position, Fig. 11(e), while avoiding collisions. All available degrees of freedom are used in this case. As one can see in Fig. 11(a)–(e), the automatic collision avoidance becomes indispensable here. To our knowledge, no other system would be able to accomplish in real time the demonstrated performance.

V. Conclusion

This paper presents a hybrid robot teleoperation system which makes use of the methodology of motion planning for whole-sensitive robots to assist the operator in generating collision-free motion in a master–slave robot arm manipulator system. The sensory information about the obstacles in the arm environment comes from a sensitive skin that covers the whole body of the arm and includes, in the current version, hundreds of active infrared proximity sensors. Unlike traditional systems where all operator commands are passed directly to and executed faithfully by the robot arm, our system combines operator commands with data from the sensitive skin such as to guarantee safe motion for the entire body of the robot arm—hence the term "hybrid." Whenever obstacles are sensed by the sensitive skin, the robot arm is automatically commanded to slide without contact along them in order to locally minimize the difference between the current position of the arm and the position commanded by the operator.

The robot arm avoids obstacles automatically and in real time and moves in a collision-free manner although no prior knowledge of the objects in the environment is available to the motion planning system; no constraints are imposed on the obstacles' shapes. Using this system, the operator is relieved of the burden of providing safety for the robot arm and the surrounding objects, and can concentrate on general strategy and control. The increase in the overall performance is especially significant in cases when the whole arm body or its large portion are subject to potential collisions. Since the difficulties the operators have in reasoning about collision-avoidance strategies tend to increase with the complexity of the system at hand, the approach is expected to be even more beneficial in systems with dual and/or redundant arm manipulators.

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