Towards Safe Real-Time Robot Teleoperation: Automatic Whole-Sensitive Arm Collision Avoidance Frees the Operator for Global Control*

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Abstract

In traditional teleoperation systems, the operator is saddled with two distinct tasks: 1) move the robot arm to its desired position, and 2) avoid obstacles that can obstruct the robot arm manipulator. To accomplish these tasks, an area of current teleoperation research is involved with providing the operator with as much input information about the task site as possible using, for example, stereo vision and feedback of contact forces. These methods presume that humans operators are capable of planning the motion for the entire body of a robot arm operating in a cluttered environment. However, studies have shown that the operators, first, cannot address both tasks in real-time, and second, are not good at generating collision-free motion. Recent results in sensor-based motion planning suggest that the collision avoidance task can be handled automatically, thus freeing the operator for global control. We propose to use for this purpose whole-sensitive arm manipulators whose whole bodies are covered with a sensitive skin sensor to detect nearby objects. The data from the sensitive skin is used along with the sensor data processing and motion planning algorithms, to avoid collisions for the entire robot arm body in an unknown or time-varying environment. The result is a highly efficient, safe and robust hybrid system in which the shift of motion control between the operator and the automatic system is done transparently and in real-time. The motion of the master arm is either executed faithfully, or, to avoid collisions, is used as general guidance for the slave arm.

1. Introduction

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, both the task of moving the arm to the desired position and the task of avoiding obstacles that can obstruct the arm are performed by the human operator. A large branch of research in this field has concentrated on aiding this process by allowing the operator to obtain as much information about the scene as possible in the form of visual and/or force feedback. More recently, this research has moved towards telepresence, where the operator is made to “feel” that he is located at the task site [1,2,4]. One unavoidable result 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.

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 camera views of 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.

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An example of this case is where a robot in earth orbit is 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 [8]. However, despite all the efforts by the human operator and the robot system designers, the collision-free motion of the entire robot arm manipulator body is still not guaranteed. 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 operators are effective in the task of planning the motion of the robot arm manipulator. 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 simple two-link planar robot arms [3], even if the entire scene is clearly comprehensible and visible. These results indicate that further assistance 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 unacceptable human injury.

We propose here a hybrid teleoperator system where the operator carries out general control and indicates intermediate goals and desired motion, whereas the generation of collision-free motion is shifted to an automatic sensor-based subsystem. This is accomplished by the addition of a sensitive skin covering the robot arm manipulator, and the appropriate data processing algorithms for motion planning and obstacle avoidance. Such a system has been built and tested in the Yale Robotics Laboratory. Our sensitive skin happens to be based on infra-red proximity sensors, though 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 motion planner so as to maneuver the arm around the obstacle to prevent collision.

The motion planning function in the teleoperated system is largely based on recent results in sensor-based robot motion planning [5,6]. The transition from the operator to computer control for obstacle avoidance is both smooth and transparent to the operator, i.e. he needn't 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 of the entire robot arm manipulator body is achieved, even in an unknown or time-varying environment.

We foresee that application of whole-sensitive robot systems will increase the efficiency and safety of generating complex motion not only in earth based systems such as unstructured factory work cells or multi-arm systems, but also in systems in outer space. In a recent study, presented to the U.S. Congress [2], it is 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 that to reduce the amount of EVA, a large number of maintenance tasks will have to rely on 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. In addition, there are attempts of developing similar technology in the area of Space Shuttle Orbiter and payload processing at Kennedy Space Center [9].

The following description of our robot teleoperation system is organized as follows. In the next section, the major components of the motion planning system are explained: 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 arm as it navigates in its environment. Then, Section 3 discusses the results of an experiment conducted with the motion planning system, accompanied with photographs of the robot arm and the skin sensor. The paper is concluded in Section 4.

2. Components of the motion planning system

The general information flow diagram of the robot teleoperation system, depicted in Figure 1, shows the interaction and hierarchy of the various units in the system; in the diagram, the decision-making (software and 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 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. 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 input device in a master-slave telerobot system, with a General Electric P5 industrial manipulator serving as the slave. Each of the major components is discussed in more detail below.

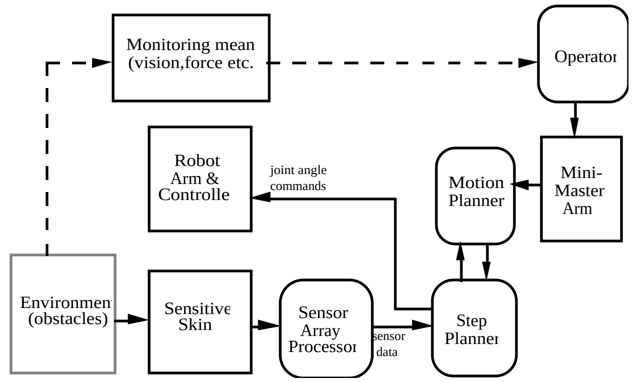

Figure 1. Information flow diagram of the robot teleoperation system.

2.1 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 Figure 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 Figure 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.

The sensor pairs are mounted on 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 details, see [5]). 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.

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

2.2 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 Figure 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 a skin sensor detects an obstacle, 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.

Safe motion is guaranteed at every step of the arm; this is made possible by 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 towards the desired target position, Figure 1.

2.3 Mini-Master Arm

The Mini-Master, Figure 3, 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 slave manipulator. Since the first three joints of the slave arm are directly controlled by the motion planning system, the angle of these corresponding joints are measured on the Mini-Master using potentiometers. Their 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.

Figure 3. Photograph of the Mini-Master Arm.

2.4 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’s overall motion. The Motion Planner commands the arm to move in free space towards 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 desired and actual position of the arm, 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 of forbidden locations of the point automaton. Despite the fact that the images of the obstacles are completely unknown to the motion planning system, the automaton may need to slide along the obstacle images when the arm is obstructed by an obstacle. This is done by moving the automaton along the tangent plane at the contact point in the configuration space generated by the Step Planning algorithm [6].

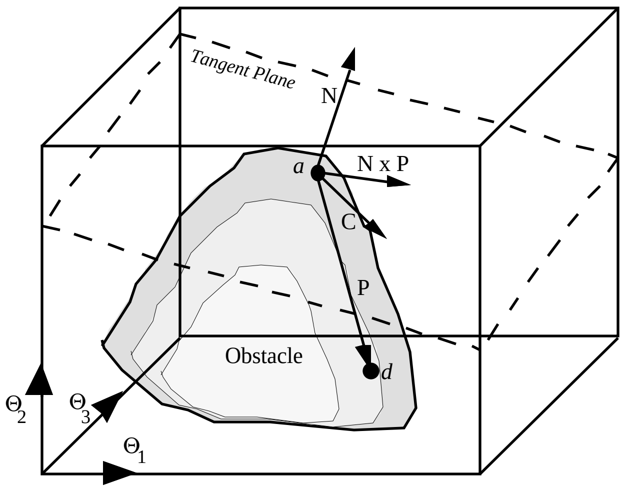

Figure 4. Motion of the automaton on the tangent plane at the contact point to the obstacle in the configuration space is along the vector C, where C = (N x P) x N; N is the normal of the tangent plane; P is the vector from *a* - the current position of the automaton, to *d* - the desired position.

During operation of the teleoperation system, the arm is controlled in one of two modes, depending on whether or not an obstacle is obstructing the slave arm. 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. However, if there is an obstacle obstructing the path to the desired position, the arm enters into Mode 2, where the automaton slides without contact along the surface of the obstacle, in order to locally minimize the Euclidean distance between the desired and actual positions of the automaton. An example of Mode 2 motion is shown in Figure 4; point *d* and *a* are the desired and the actual positions of the automaton respectively. In this case, the automaton is obstructed by the obstacle and slides along the vector C= (N x P) x N, where N is the normal of the tangent plane and P is the vector connecting points *a* and *d*. At every step along the obstacle's surface, the vectors N, P and C are found in order to cause the automaton to slide along the obstacle. This sliding continues until the vectors N and P are co-linear, thus when the Euclidean distance between points *a* and *d* can no longer be locally minimized.

We emphasize that no conflict between the "desires" of the operator and the automatic planning system can ever take place - despite the fact that no explicit control priorities are assigned between the operator and the motion planning system. The command given to the robot arm while it slides along the obstacle is based on both the data from the sensitive skin and the command from the system user. The user need not even pause to push a button in order to avoid the obstacle. The switch between Mode 1 and Mode 2 is completely automatic, transparent, and smooth, allowing the robot arm to execute safe motions continuously at all times. The task of avoiding obstacles has been completely "off-loaded" from the operator, allowing him to better concentrate on the task at hand.

3.1 Experimental validation

In a typical experiment, several objects of planar and curvilinear shape completely unknown to the motion planning system are placed in the reach envelope of the slave robot arm. The operator guides the robot 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, the Master Arm is moved 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.

Figure 5a. Experimental validation of the hybrid robot teleoperation system.

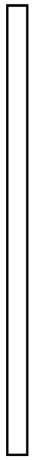

Figure 5b.

Figure 5c.

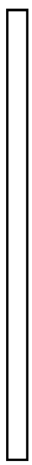

Figure 5d.

Figure 5e.

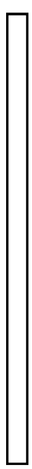

Figure 5f.

Figure 5g.

An example of such an experiment is shown in Figure 5. Only one axis of the Mini-Master has been moved in the sequence of photographs in the figure, while the other axes were fixed. Two obstacles are placed in the reach envelope of the slave arm. In Figure 5a the motion of the slave arm is unobstructed, and so it faithfully replicates the commands given by the Mini-Master Arm. The right most object is encountered first, Figure 5b. Due to the object's shape, the slave arm is able to slide over it, see Figures 5c and 5d, 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 Figure 5e 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, Figure 5f. Because of the object's concave shape, the arm does not move further as the distance between the desired and actual position of the slave arm can no longer be locally decreased, and halts at some distance from the surface of the obstacle. As one can see from Figure 5g, the motion planning algorithm uses the data from the sensitive skin to make the arm slide along the surface of the obstacle and thus “refuses” to collide with the obstacle.

More complex experiments have been also carried out, in which, besides fixed obstacles, a moving obstacle - a human - was present in the robot work space, the operator was further removed from the scene, and his viewing of the scene was largely blocked by one of the obstacles; those experiments exhibited performance similar to that above (for more detail, see [10])

4.1 Conclusion

This paper discusses a hybrid robot teleoperation system which makes use of a sensitive skin and its associated data processing and motion planning algorithms for assisting the operator in generating collision-free motion of a robot arm manipulator. Unlike traditional systems where all operator commands are passed directly to 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. Whenever obstacles are encountered by the sensitive skin, the robot arm is commanded to slide without contact along them in order to locally minimize the difference between the commanded and actual position of the arm. The robot arm avoids obstacles automatically and moves in a collision-free manner although no prior knowledge of the objects in the environment is known to the motion planning system. Using this system, the operator is relieved of the burden of providing obstacle avoidance for the slave robot arm and can concentrate on general strategy and control.

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