Proceedings of the 5th IEEE
International Symposium on Assembly and Task Planning
Besançon, France • July 10-11, 2003

Collision-free path planning of a telerobotic manipulator based on swept volume of teleoperated manipulator

Tsutomu HASEGAWA, Kousuke NAKAGAWA, Kouji MURAKAMI
Department of Intelligent Systems,
Graduate School of Information Science and Electrical Engineering
Kyushu University
6-10-1 Hakozaki Higashi-ku Fukuoka 812-8581 JAPAN
{hasegawa, nakagawa, mkouji}@irvs.is.kyushu-u.ac.jp

Abstract

A new approach to collision-free path planning for a telerobotic manipulator is proposed. Using swept volume of a slave manipulator tele-operated by a human operator, on-line transition to autonomous teleoperation from master-slave manipulation is achieved without any geometric model of an environment. This feature enables wider application to unstructured environment.

1 Introduction

Mater-slave teleoperation is an only possible means to execute various skillful tasks in a hazardous and unstructured environment when no a priori knowledge about the task and the environment is available. However, it is very tedious and tiresome for a human operator to carefully manipulate a master arm to control a slave arm executing a task in an exotic remote environment cluttered with obstacles. Although various techniques of the virtual reality may help the operator reducing the burden of manual control of the master arm, the operator is still responsible to all the motion of the manipulator[1]. This paper proposes a new approach to automatic motion planning for a remote slave manipulator, aiming at on-line transition to autonomous teleoperetion from master-slave manipulation.

There have been many research works on autonomous planning of collision free motion of the robotic manipulator [2][3]. Geometric environment model is indispensable for any existing motion planning algorithm. However, it is still quite difficult to generate a reliable geometric model of a real unstructured environment using computer vision. There are too many difficulties for the computer vision process : a very large difference of optical surface property from a metallic mirror to a dark colored object, shadow and illumination, occlusion, dynamic change of object pose etc.

The basic idea behind our approach proposed in this paper is to directly generate a free space model without generating object models using computer vision.

In the master-slave tele-operation process, the human operator visually recognizes a work space structure through TV monitors, plans manipulation sequence of objects, and then carefully manipulates the master arm to execute the required task while observing the motion of the remote slave manipulator. Collision avoidance of the whole arm of the remote manipulator with a load is visually achieved by the human operator.

In this process, the actual trajectory in the joint space of the remote manipulator is directly obtained from output of joint encoders. In the Cartesian space, each part of the manipulator occupies certain definite volume and sweeps volume in the 3D free space along the motion trajectory. Our idea is to exploit this swept volumes by the slave manipulator in order to construct 3-D Cartesian free space structure without constructing structure of the occupied space by 3-D object using computer vision.

After execution of certain tasks, record of the actual collision free trajectory in the joint space is accumulated. In the joint space(configuration space), trajectories are one-dimensional segments composed of lines and curves and can not cover areas. Once the records are transformed into 3D collision free swept volume in the Cartesian workspace, they covers 3D continuous volumes which may contain swept volume of different trajectory of the manipulator.

Imagine two similar but different motions of the manipulator executed very closely: in Cartesian 3D space, part of the swept volumes overlap when the manipulator moves along the two different trajectories, however, two trajectories are separated in the configuration space. In the Cartesian space, we can easily find a set of collision free trajectories connecting the two motions mentioned above, however, we can not find any connecting trajectory only based on the executed trajectories in the configuration space.

This explains the meanings of mapping trajectory in the configuration space into the swept volume in the Cartesian space. From the swept volume in the Cartesian space, collision free volume is recovered in the configuration space.

This paper is structured as follows. Section 2 describes basic principle to reconstruct 3-D empty space in a real remote workspace. In section 3, a method of planning collision-free path of the manipulator is proposed using the reconstructed 3-D empty space. Detail of the system implementation is explained in section 4. Simulation results of path planning are shown in section 5. Then we discuss possible scenarios of application and problems left to be solved in section 6. Section 7 is a conclusion of this paper.

2 Reconstruction of 3-D Empty Space

A real 3D remote work space is composed of occupied space by obstacles and empty space. In our method, the empty space is obtained as a set of swept volume of the slave manipulator tele-operated by human operator under his visual observation. Thus the more the slave manipulator moves around in the work space, the more empty space structure is obtained.

Since the swept volume by the manipulator has complex shape, it is very difficult to explicitly and precisely describe its surface shape. Instead, we use discretized representation by cubic voxels in 3D workspace. We have developed methods of recursive subdivision of 3-D space and hierarchical interference check to efficiently describe the swept volume. In each subdivision process, a cubic voxel is divided into 3 by 3 by 3, producing 27 cubic voxels. This subdivision is repeated until sufficient resolution is obtained.

An obtained motion trajectory of the slave manipulator controlled by the human operator is discretized into a sequence of points in C-space, and then occupied voxels by the manipulator at each point is computed by using occupancy checking and integrated into the swept volume. Complementary space to the swept volume is regarded as inhibited space to pass through for the manipulator. Collision check of the manipulator in the path planning phase is made by occupancy check of the manipulator in this inhibited space.

In the teleoperation phase, the operator should know how much the empty space is structured by his teleoperation. We have introduced an acquisition index of the empty space for this purpose. This index enumerates number of empty voxels actually swept by the manipulator. Since the total volume of workspace of the manipulator is known especially when there is no obstacle in it, the acquisition index is useful for the operator to switch the system from teleoperation-mode to autonomous mode.

3 Collision-free path planning

3.1 Generation of roadmap

Once the empty space of the working environment is described sufficiently in the 3D Cartesian space, the corresponding structural feature in the configuration space is extracted to efficiently plan the collision free motion of the slave manipulator. For this purpose, we use the Randomized Road Map method[4]. This method is effective when multiple different motions are executed by a slave-manipulator in a same work space.

The roadmap is an undirected graph $R = (N, E)$, constructed in a probabilistic way. The nodes in N are a set of collision-free configurations of the manipulator. The edges in E correspond to a set of collision-free path connecting two nodes in N. Beginning from a vacant graph $R = (N, E)$, the process of constructing the roadmap repeats following steps: a random collision-free configuration c is generated and added to N, and then the process tries to connect c to nearby node n in N. Once a collision-free path connecting c and n is found, the edge (c, n) is added to E.

3.2 Searching for a collision free-path

Given an initial configuration Ic and a goal configuration Gc of the manipulator, a collision free path is planned in three steps.

(1) Searching for a path from the initial configuration Ic to a nearby node Ni in the road map

(2) Searching for a path from the goal configuration Gc to a nearby node Ng in the road map

(3) Planning a path connecting Ni and Ng in the road map

4 System Structure

We have developed a prototype teleoperation system. In our current implementation, a remote slave manipulator and its working environment are substituted by a geometric simulator. Fig.1 shows the system architecture. The system is composed of following components.

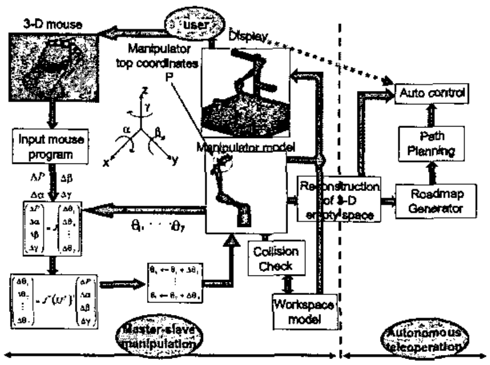

Figure 1: system architecture

(1) Master manipulation system:
The master manipulation system is composed of a 3-D mouse as a master controller to control 6 DOF pose of the end effecter of a remote slave manipulator, and a graphic display to usually monitor the remote slave manipulator

(2) Tele-manipulation site:
Tele-manipulation site is simulated by Geometric simulator composed of an environment model and a manipulator. We use a 7-DOF manipulator (PA-10, Mitsubishi Heavy Industries) as a slave manipulator. Fig.2 shows the remote manipulator together with the world coordinate frame of its work space. The manipulator is equipped with 3-fingered hand. Length of the movable part of the manipulator is $1365mm$ when extended straightly including the hand.

Figure 2: PA-10

(3) 3D free space model:
A remote work space is defined as a cubic space whose size is $2000mm$ x $2000mm$ x $2000mm$. Each edge of the cube is aligned in parallel with x, y, z axis of the world coordinate system. The center of the cube is located at (300 0 1000). The work space is recursively divided into 3 x 3 x 3 voxels and hierarchically structured from single cube in level 0 to 531,441 voxels in level 4. Size of a voxel in level 4 is approximately $25mm$ x $25mm$ x $25mm$. Since actually reachable space by the manipulator is different from the cubic space in level 0, 221,303 voxels are effective among 531,441 voxels in level 4 when there is no obstacle in the workspace.

(4) Randomized Roadmap generator:
This part is composed of a randomized point generator in C-space, a local planner for a collision-free path connecting a point in C-space to a roadmap under construction, and a controller of construction process of the roadmap. For each new point randomly generated in the configuration space, all those nodes within a threshold Euclid distance (80 degrees in the current implementation) are picked up from the roadmap. The local planner then tries generating a linear collision-free path connecting the newly generated point to each selected node of the roadmap. Binary collision check along the line path segment is made until distance between 2 points is less than 10 degrees. Hierarchical collision check is made using 3D model of the manipulator and the 3D hierarchical free space model. All the collision-free path thus generated is added to the roadmap.

(5) Collision Free Path Planner:
The same local planner is used to plan a collision-free path from a given initial configuration to the roadmap and from a given goal configuration to the roadmap. A* algorithm is used for planning a path in the roadmap.

5 Simulation Results

We have generated a tele-manipulation site in the simulator. Using the 3-D mouse, a human operator moved the slave manipulator.

In our first simulation, we show a rather simple case to visually explain the principle of our approach. Fig.3 shows the swept volume of the manipulator and the reconstructed empty space. The operator moves the manipulator from a configuration $(90, -45, 0, 0, 0, 0, 0)$ to another one $(90, 0, 0, 0, 0, 0, 0)$ linearly, and then to the final point $(90, 45, 0, 0, 0, 0, 0)$. Given an initial configuration point $(90, -45, 0, 0, 0, 0, 0)$ and goal point $(90, 45, 0, -120, 0, -90, 0)$, a new trajectory is automatically planned as shown in Fig.9 using the reconstructed empty space. Total number of the swept voxel in level 4 is approximately 15,000 while total possible workspace is less than 221,303 voxels.

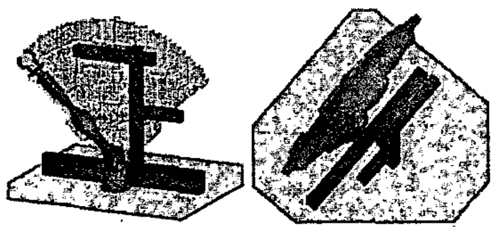

Figure 3: swept volume (1) : (a) oblique view, (b) top view

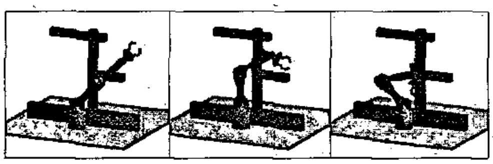

Figure 4: new trajectory

Fig.5 shows the working environment and the manipulator together with the computed voxels indicating the swept volume by the slave manipulator. In this case, 50,320 voxels in level 4 are swept by the slave manipulator. Therefore the acquisition index is 0.23 (50,320 swept voxels / 221,303 effective voxels).

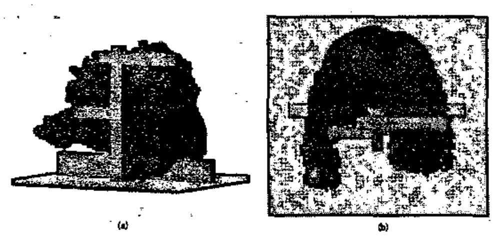

Figure 5: swept volume (2): (a) oblique view, (b) top view

Based on the swept volume, the system generated a roadmap in the configuration space. It took $6.3s$ in average of 50 times to randomly generate 5000 collision-free configurations, and then it took $138.6s$ to generate the roadmap composed of 20000 edges connecting these configurations.

Given an initial configuration and a goal configuration, a path was planned in $6.9s$ of computation time(Fig.6). Fig.7 shows another example of a planned path with a different combination of initial and goal configurations. For these simulations, we used a PC (Pentium III $1GHz$ CPU).

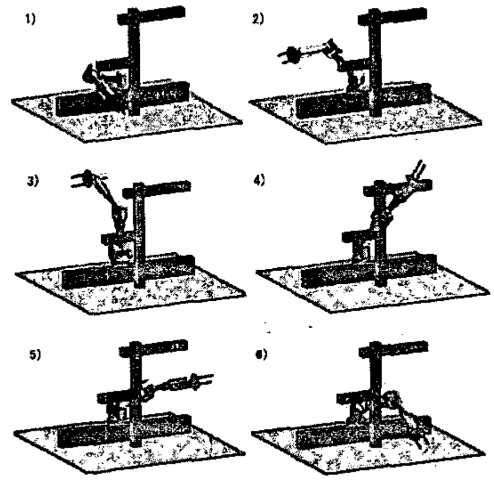

Figure 6: planned path (1)

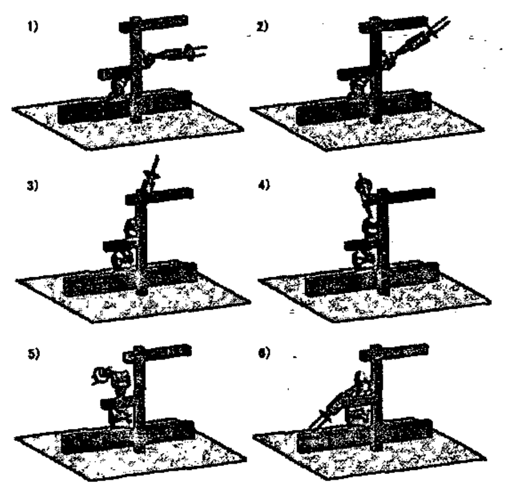

Figure 7: planned path (2)

Fig.8 shows a result of application to a different environment. Fig.9 shows an example of planned path.

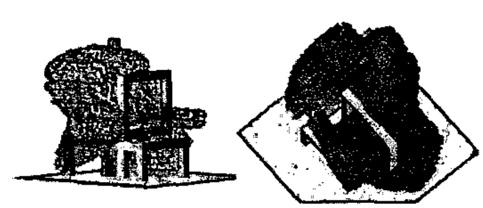

Figure 8: swept volume (3): (a) oblique view, (b) top view

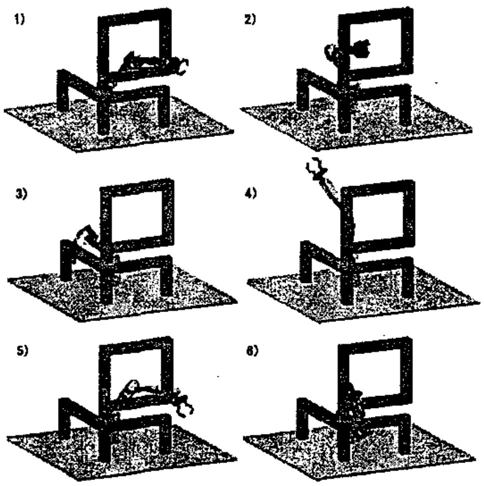

Figure 9: planned path (3)

6 Discussions

Exploiting trajectories of a remote slave manipulator tele-operated by a human operator, structure of the empty space is reliably and conservatively obtained without additional computer vision system. This method would lead to an advanced tele-operation system: any task would be immediately executed by a human operator and then on-line transition can be achieved to an autonomous tele-operation from a master-slave manipulation.

Possible scenario of application includes an emergency operation in hazardous man-made environment such as chemical plant and nuclear power plant. Handling a valve on a pipe within a complex piping structure would be a typical task composed of open/close, disassembly, exchange of parts, and re-assembly of the valve. At the beginning, a human operator carefully controls the manipulator to execute initial part of the task and then autonomous tele-operation takes over the rest of the task.

Although a local vision system must be required for the autonomous manipulation, the vision system would be rather simple. The global structure of the environment is already known from swept volume of the teleoperated slave manipulator. Therefore, the vision system only needs to recognize an object to be manipulated and its surrounding space when the end effector approaches the object.

Application of such an advanced teleoperetion system to a dynamically changing environment is out of scope of this paper, however there are still problems left to be solved in the autonomous tele-operation mode in a static working environment:

(1) Developing high-level command : how to specify goal configuration?

(2) Coping with change of space structure made by manipulation : how to synchronously modify the 3D free space model and the roadmap?

Information of task context, interactive oral teaching of symbolic name of an object being manipulated, and introducing pointing device into a real remote environment[5] would help solving problems. Research on these topics is now under way.

7 Conclusion

A new approach to automatic motion planning for a remote slave manipulator in teleoperation system is proposed. Instead of explicitly constructing a geometric model of the work space, the swept volume of a slave manipulator tele-operated by human operator is structured to be an empty space model in 3D Cartesian space. Then a collision-free roadmap is generated in the configuration space of the manipulator using this empty space model. Given an initial configuration and a goal configuration, a collision-free path is planned passing through the swept volume of the manipulator.

This approach is applicable to a tele-manipulation system in an unstructured and hazardous environment. Although initial operation by the human operator is required, the autonomous teleoperation will take over in the later process of the tasks. Several problems and their solutions are discussed.

References

[1] Y.Tsumaki , M.Takahashi , W.K.Yoon and M.Uchiyama, "Virtual Rader: An Obstacle Information Display System for Teleoperation", Proc.2002 IEEE ICRA, pp.1185-1190 (2002)

[2] J-C.Latombe, "Robot Motion Planning", Boston, Kluwer, (1991)

[3] Y.K.Hwang and N.Ahuja, "Gross Motion Planning - A Survey", ACM Computing Surveys, 24, 3, pp.219-291 (1992)

[4] L.E.Kavraki , P.Svestka , J-C.Latombe , and M.H.Overmars , "Probabilistic Roadmaps for Path Planning in High-Dimensional Configuration Spaces", IEEE Trans. RA, Vo.12, No.4, pp.566-579, (1996)

[5] T.Hasegawa, T.Suehiro and K.Takase, "A Robot System in Unstructured Environment Based on an Environment model and Manipulation Skills", Proc. 1991 IEEE ICRA, pp.916-923, (1991)