3-D WORLD MODELING BASED ON COMBINATORIAL GEOMETRY FOR AUTONOMOUS ROBOT NAVIGATION

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ABSTRACT

In applications of robotics to surveillance and mapping at nuclear facilities the scene to be described is three-dimensional. Using range data a 3-D model of the environment can be built. First, each measured point on the object surface is surrounded by a solid sphere with a radius determined by the range to that point. Then the 3-D shapes of the visible surfaces are obtained by taking the (Boolean) union of the spheres. Using this representation distances to boundary surfaces can be efficiently calculated. This feature is particularly useful for navigation purposes. The efficiency of the proposed approach is illustrated by a simulation of a spherical robot navigating in a 3-D room with static obstacles.

I. INTRODUCTION

This section contains an overview of the potential benefits that are achievable with current robotic systems and needed improvements to those systems for effectively applying robotics in nuclear power plants.

I.1. Justification of Using Robots in Nuclear Power Plants

An important motivation for considering the use of surveillance/inspection robots at nuclear power plants is to reduce the radiation exposure to workers.[1] Experience with robotics at automated manufacturing plants shows that the man-hours required to perform tasks can also be decreased, while work quality is improved.

The most widespread robotic applications have been to work tasks that are hazardous, repetitious and/or involve simple pick/place or path control motions. In nuclear power plants, surveillance/inspection operations involve looking and listening for leaks and abnormal equipment operation, measuring radiation and contamination levels, checking the position of valves and indicators, and reading gauges. The relatively high radiation levels, humidity and temperature in the containment during operation place a considerable physical burden on operators and maintenance personnel. In addition, operators normally have to wear cumbersome air breathing equipment that further restricts their physical ability to stay for long periods in such an environment while making precise observations. A mobile robot might perform a number of tasks now undertaken by humans, e.g., the robot could take temperature, humidity and radiation readings, make visual inspections in high radiation areas, and inspect structural bolted components at close range.

I.2. Current Capabilities/Use of Robotics

The current robot systems utilize teleoperated control (Master/Slave) systems.[2,3,4] They have locomotion, but lack efficient path planning with collision avoidance capability. A major problem encountered with remotely controlled vehicles within large rooms is disorientation of the operator. That is, the operator can observe the scene transmitted from the vehicle cameras, but there is sometimes no frame of reference indicating the location of the vehicle within the room, or the direction in which the cameras are aimed. In addition, the 3-D environment in which the robot operates is (usually) only partially known. Commercially available sensors and measuring equipment can be used to perform a broad range of tasks including detection of steam/water leaks, reading instruments and gauges, measuring radiation level, detecting abnormal noises, overheating and thermal insulation leaks, etc. The acquired data (for example video) are currently transmitted to the human operator for decision making, without preprocessing. Such total reliance on the remotely located operator is undesirable because the time required to perform surveillance work could be eight to ten times longer as compared

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to a human worker[5] completing the task directly.

I.3. Needed Improvements for Robotic Systems

The next generation of robotics systems should have a 3-D world modeling capability based on sensor derived data.[6] This capability is necessary for the following tasks:

a) Facility mapping (cells in the radwaste systems, equipment rooms, etc.) needed during decommissioning and planning for modifications at commercial nuclear power plants, since accurate as-built drawings may not be available or currently accurate. The 3-D model based on sensor derived data may be used to update the a-priori geometric information.

b) Immediate post-accident inspections.

c) Autonomous navigation with obstacle avoidance.

An efficient man-machine system should have data processing and learning capability. This option will provide the human operator with improved capability for supervisory control. Finally the future autonomous robots should have efficient, sensor guided navigation and manipulation algorithms including obstacle detection and avoidance, and trajectory path planning.

II. 3-D EXTERNAL WORLD MODELING

An autonomous robot must have sensory capability to deal with unknown or partially known environments. The sensor derived data need to be processed to an appropriate internal representation of the external world. The external world to be described is fundamentally three-dimensional, involving object occlusion. Most computer vision research performed during the past twenty years has concentrated on using intensity images as sensor data. The imaging hardware (cameras) for these studies typically projects a three-dimensional scene onto a two-dimensional image plane, thus providing a matrix of gray level values representing the scene from a given viewpoint. These values indicate the brightness at points on a regular spaced grid and contain no explicit information about depth. Methods that use intensity information only for deriving 3-D structure are usually computationally intensive. This computationally expensive processing arises due to the fact that correspondence of points between different views must be established and a complex system of nonlinear equations must be solved.[7,8,9,10,11]

In recent years digitized range data have become available from both active and passive sensors, and the quality of these data has been steadily improving.[12,13,14] Range data quantify the distances from the sensor focal plane to an object surface. Since depth information depends only on geometry and is independent of illumination and reflectivity, intensity image problems with shadows and surface markings do not occur. Therefore, the process of representing 3-D objects by their shape should be less difficult in range images than in intensity images. The problem addressed by this paper is the external world modeling using range data. Unique requirements for such a model are:

a) Allow representation of a general 3-D, unknown or partially known environment, based on sensor data.

b) Minimal fast memory for storage.

c) Efficient for navigation purposes (efficient distance calculations to 3-D surfaces).

d) Suitable for learning schemes.

Since the range image shows only the "viewed" side of each object and objects may partially or completely occlude one another, a surface boundary representation is the natural choice for the proposed model.

II.1. Representation Methods of 3-D Surfaces-Review

A wide variety of techniques has been developed for representing 3-D surfaces for digital computing purposes. The simplest boundary representation is using n-sided planar polygons (triangles, quadrilaterals, etc.) which can be stored as a list of 3-D node points along with their relationship information. Arbitrary surfaces are approximated to any desired degree of accuracy by using many planar polygons. This type of representation is popular because model surface area is well defined and all object operations are carried out using piecewise-planar algorithms. The next step in generality is obtained using quadratic surface boundary representations. More advanced techniques for representing curved surfaces with higher order polynomials or splines are mentioned in the computer graphics and CAD literature.[15,16,17,18] There are many different techniques of this type; most are generally not very compact in terms of data storage, nor are they computationally efficient in calculating distances to boundary surfaces.

II.2. Representing 3-D Surfaces Using the Combinatorial Geometry

The basic problem addressed by this paper is one of representation. The proposed approach is based on the Combinatorial Geometry (C G) method[19] which is widely used in Monte Carlo simulation of particle transport in 3-D geometries. In C G (also known as Constructive Solid Geometry (CSG) in computer graphics and CAD literature) solids are represented as combinations of primitive solids or "building blocks" (i.e., spheres, cylinder, boxes, etc.) using the Boolean operations of union, intersection and difference. The storage data structure is a binary tree where the terminal nodes are instances of primitives and the branching nodes represent Boolean operators. Any 3-D known object can be represented by a (Boolean) combination of primitive solids. This representation is especially suitable for describing a-priori known parts of the environment. An example of describing an object composed of two boxes, one of them with a cylindrical hole is illustrated in Fig. 1. The result is a concise, unambiguous and complete representation of the object volume and boundary surface.

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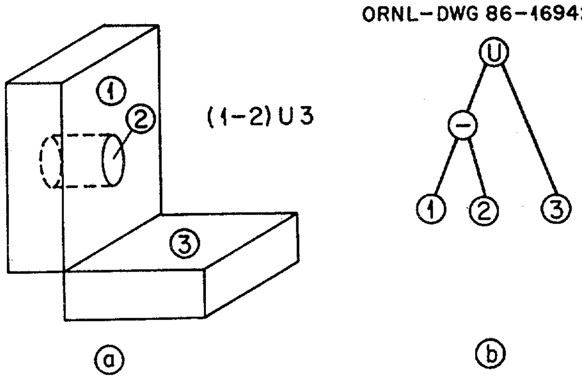

Fig. 1. Representing a 3-D object using Combinatorial Geometry.

a - given object and its C G representation.
b - the storage data tree.

The result of a range scan is a matrix of distances from the sensor focal plane to an object surface. In other words, the coordinates of discrete points on the "visible" parts of the boundary surfaces of different objects in the external world of the robot, are known. Let α be the (small) angle between two successive "reading" directions of the sensor. First, each discrete point i, is surrounded by a small solid sphere with a radius, $r_i = \max(R_i \sin\alpha, \Delta R_i)$ is the range to point i, and ΔR_i is the associated measurement error. Then, the approximate 3-D shape of the visible boundary surfaces is obtained directly by taking the union of all the spheres (see Fig. 2).

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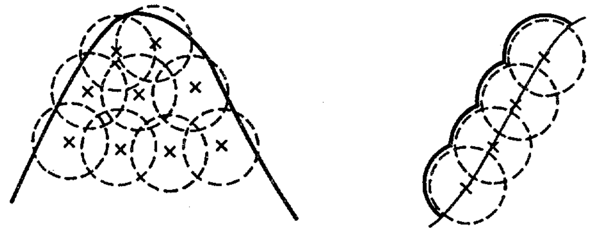

Fig. 2. Describing the shape of 3-D objects using spheres.

The reason for using spheres is to keep the representation as compact as possible. Describing the sphere for a particular discrete point in space means adding only one additional parameter (the radius) to the coordinates of the discrete point which are provided by the sensor. The radius r_i is defined as $r_i = \max(R_i \sin\alpha, \Delta R_i)$ to avoid the appearance of "holes" in the geometry and to take into account the range uncertainty. Using this definition for r_i, neighbor spheres are highly overlapping one another and the boundary surface of the union of all spheres is continuous (without holes) from the robot's point of view. Finally, it is obvious that using the "sphere" procedure, the shape of the boundary surfaces is distorted. However, the distortion is proportional to the range to each point. In other words, the resolution of the model is improved as the range to the surface is decreased.

II.3. Distance Calculation in C G Representation

A very useful feature of the C G representation is its efficiency in calculating distances to 3-D surfaces in a desired direction. Observing discontinuities in the range data greater than the maximum size of the robot, the scene is partitioned in many different zones. A zone is defined as the union of small spheres located between two successive discontinuities in the range data. Using the storage data structure mentioned in Section II.2, two tables are defined: the first one includes the spatial location of the small spheres; the second one identifies the different zones in terms of these spheres. The distance to 3-D surfaces in a desired direction from a given point is calculated in two steps:

1) Each zone is surrounded tightly by a box (rectangular parallelepiped). Since the boxes are approximate bounding configurations, intersections of a given ray with a box does not necessarily imply intersection

with any particular sphere. In addition, the different orientations of the sphere clusters imply that bounding boxes can intersect and therefore multiple boxes may have to be checked for penetration by a given ray. The box (boxes) penetrated by the ray is determined by calculating the intersection points between the boxes and the ray. A list consisting of the boxes physically penetrated by the ray, along with all their adjacent boxes, is defined. The corresponding list of zones is used to determine the penetration point.

2) Determine the small sphere penetrated by the ray and calculate the penetration point. This is done by considering only the spheres included in the zones listed in the first step. Using this approach, only a small number of spheres are checked for penetration, and therefore significant computation time is saved.

It should be mentioned that the boxes surrounding the zones are used only internally during distance calculations and they are not affecting the geometric description of the 3-D surfaces. The range data provided by the sensor quantify the distances from the sensor focal plane (the center of the robot in our model) to object surfaces. During path planning, "tentative paths" are checked for potential collision by calculating the distances to object surfaces from scattered points on the robot's surface in the desired direction. These distances can be effectively calculated by using the C G representation, and the procedure outlined above.

III. A HEURISTIC NAVIGATION ALGORITHM

The efficiency of the proposed model for representing the external world is illustrated by testing a simple navigation algorithm for a simulated spherical robot in a 3-D room with several static obstacles. The robot is assumed to move in a plane parallel to the floor, along straight lines. The origin of coordinates is arbitrarily located at the robot's starting position. The goal coordinates are known a priori. No other information concerning the external world is known a priori. The external world geometry, the robot starting position, and the goal location are illustrated in Fig. 3. The radius of the spherical robot is 3 cm. The plane of motion is 30 cm off the floor. The navigation algorithm proceeds as follows:

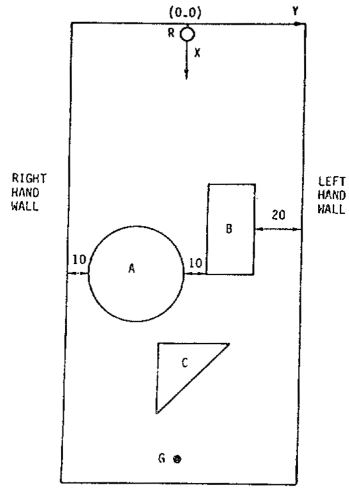

Fig. 3. The geometry of the room. The dimensions are specified in cm.

R - The initial position of the robot. (5,0,30)
G - The goal position (190,0,30)
A - Sphere; center at (110,-20,30); radius 20
B - Box; dimensions: 40x20x90
C - Prism; dimensions: 30x30x90
Room dimensions: 200x100x100

1) The robot begins a simulated 3-D range scan. In other words, the distances from the robot's center to object surfaces are calculated. It is assumed that the exact range information is sampled in discrete directions, at steps of 3° each, for a complete 360° azimuthal scan and a 30° polar scan (10° down and 20° up the horizon). The obtained range matrix contains 1200 numbers quantifying the distances to 1200 points on the boundary surfaces of objects in the external world.

2) The range data are used to represent the external world geometry, following the approach described in Chapter II.

3) If the entire volume of the robot may reach the goal without collision, the mission is accomplished. If not, several tentative paths are defined, where discontinuities in the range data are observed (see Fig. 4). Let $\vec{r}_i$ and $\vec{r}_{i+1}$ be two successive readings of the sensor. If the distance $|\vec{r}_{i+1} - \vec{r}_i|$ is greater than the maximum dimension of the robot (the diameter in our case) then $\vec{R}_{i,i+1} = [\vec{r}_i + \vec{r}_{i+1}]/2$ is defined as a tentative path.

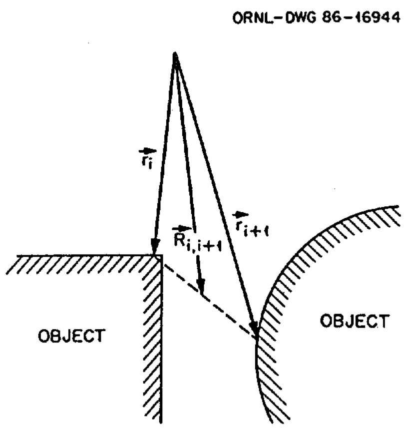

Fig. 4. Defining tentative paths.

4) Each tentative path is tested for potential collision by calculating the distances to object surfaces from nine points on the robot's boundary surface in the desired direction (see Fig. 5). Let $DIST_j$; j = 1,2...9, be the distance to collision from point j in direction $\vec{R}_{i,i+1}$. The minimal distance, min ($DIST_j$), is the distance the robot can travel in this particular direction ($\vec{R}_{i,i+1}$).

5) An optimal path is chosen among the tentative paths, such that $\vec{R}_{i,i+1}$ is nearest to the goal.

6) If the robot makes a backward move, it records the previous location as another obstacle with an equivalent size to the robot. In this way, the robot is gradually "squeezing out" the dead ends and "works" into open areas where larger moves are possible.

7) The robot moves 70% of the way to the chosen location and reorients towards the goal. The robot's coordinates are adjusted accordingly and a new simulated 3-D range scan begins (step 1).

The minimal distance of the robot surface to any object must be greater or equal to 1 cm, otherwise a collision is declared.

Figures 6-9 illustrate the robot's position in the "visible" external world. Only the plane of motion is depicted in the figures.

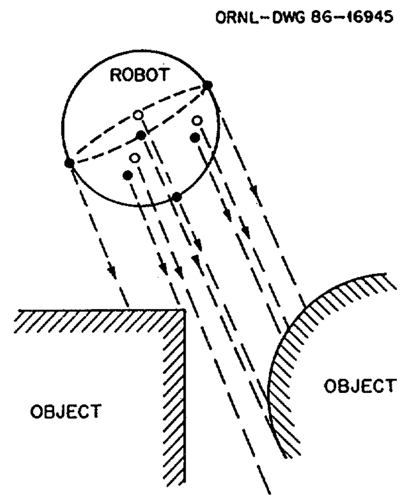

Fig. 5. Testing a tentative path for collision.

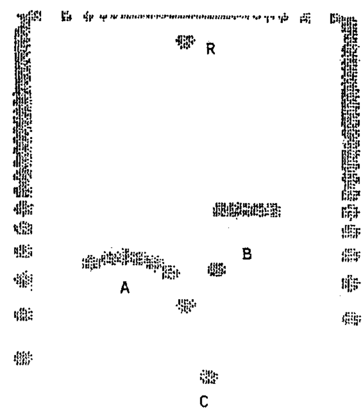

Fig. 6. The external world as "viewed" by the robot from its initial position.

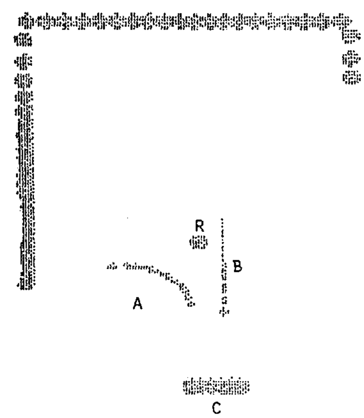

Fig. 7. The robot moves through the passage between the box and the sphere.

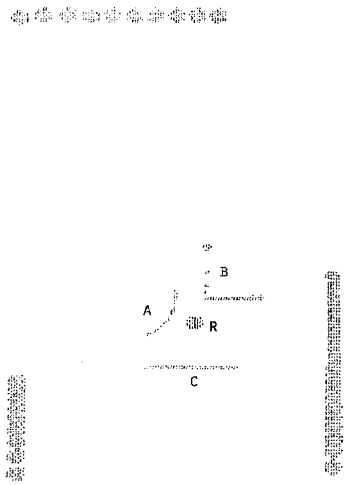

Fig. 8. The robot completes its motion through the passage between the box and the sphere.

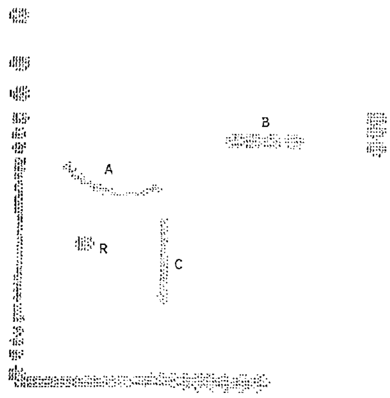

Fig. 9. The robot moves through the passage between the sphere and the prism. Finally, he can "see" directly the goal.

IV. CONCLUSIONS

The next generation of robotics systems should have a 3-d world modeling capability based on sensor derived data. This capability is necessary for facility mapping, immediate post-accident inspections, autonomous navigation with obstacle avoidance, and for increasing the reliability of operation in a combined supervised/autonomous mode.

The proposed approach for modeling the external world using the Combinatorial Geometry was found promising for navigation purposes with obstacle detection and avoidance. The computation time per "picture", including the simulated range scan, modeling the geometry, trajectory planning and plotting the plane of motion was 5 to 15 sec CPU time of CYBER 180-840 Computer, depending upon the number of tentative paths considered. Most of the computation time is used for plotting the plane of motion and for calculating distances in a given direction from discrete points on the robot boundary surface. These calculations can be done independently and therefore performing the same calculations on a parallel or concurrent computer may significantly reduce the computation time.

Future work using the proposed external world model will focus on the following issues: Experiments involving partially known three-dimensional environments, updating the geometry using the sensor data, integrating the sensor data from different range scans, the robot's self location problem and the problem of dynamic environments.

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