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A Field Prototype of a Robotic Pavement Crack Sealing System

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ABSTRACT

Highway maintenance automation presents substantial opportunities to reduce labor costs, improve work quality, and decrease worker exposure to roadway hazards. A research project at Carnegie Mellon University and the University of Texas at Austin has demonstrated an automated method for filling pavement cracks that is a cost effective application of construction robotics. A field prototype mechanism has been constructed and demonstrated that emulates a proposed production system. This paper describes the design of the field prototype as well as experiments that were conducted to evaluate the robustness of the crack detection and manipulator trajectory planning algorithms. Based upon the results of these field trials and additional economic analysis, the feasibility of a production system is evaluated.

1. INTRODUCTION

While many roadway construction and maintenance tasks have been mechanized, few have been automated. Maintenance procedures remain labor intensive, expensive and unsafe. Recent advances in robotic technology and the related experience in manufacturing facilities suggests that greater automation may be extremely beneficial[1]. Relevant technological improvements include new sensors, faster computers, better sensor interpretation algorithms and more flexible manipulator hardware. In this paper, we describe the development of a prototype robotic pavement crack sealing system which has been demonstrated in field trials. The field prototype was developed in the second phase of an ongoing project funded by the Strategic Highway Research Program.

Automation of crack sealing operations is of considerable interest for several reasons. First, crack sealing is a widespread and common operation in the United States. If even modest cost savings could be achieved in crack sealing operations, the total savings would be substantial. Second, automated crack sealing may achieve improved quality over existing field operations, so that the need for maintenance operations may be reduced over time. Finally, automated crack sealing would reduce the exposure of maintenance workers to injury and accident.

Automated pavement crack sealing is a technically challenging operation for several reasons. Since pavement cracks are irregular in features and extent, simple numerically controlled devices cannot be used directly. Some means of perceiving crack location and dynamically controlling maintenance equipment is required. Moreover, crack sealing is undertaken under field conditions which may involve extremes of temperature, precipitation and debris. Maintenance of the equipment used in roadway work varies considerably in quality, therefore robust, reliable and inexpensive equipment is required.

In the next section, the justification for automated crack sealing is analyzed in greater detail. The system concentrates on automating one portion of the crack sealing operation, namely the cleaning and sealing of cracks which may or may not have been previously routed. Cleaning and sealing were deemed to be more amenable to automation given the current state of technology. The design and operation of the system are described in the following sections. Field trial results are used to illustrate the concepts involved. Conclusions and recommendations are presented in the last section.

2. JUSTIFICATION FOR A ROBOTIC CRACK SEALER

Many states and provinces routinely seal cracks as a maintenance activity on an "as required" basis. The expenditures on this activity often represent a significant portion of pavement maintenance budgets. To obtain an accurate picture of crack sealing practices and expenditures the 50 states were surveyed. Responses were received from 38 state transportation departments. The survey responses indicated considerable variability in crack sealing practice, costs, and expenditures. For example, eight states spent more than 2 % of their annual maintenance budget on crack sealing. For the 38 states responding to the survey a total of $47.6 m was spent on crack sealing in 1990. Of these costs, labor accounted for 61%.

Further analysis of the data obtained can provide some crude estimates of the benefits to be realized from automating crack sealing. The average crew size for crack sealing is 7. The automation of the procedure could yield a savings of 3 laborers. Assuming the crew works on sealing 25% of the time during 6 months of the year, the expected labor savings is $10,000 per year per crew based on an average labor rate of $12 per hour. This represents 15% of the sealing costs. The other side of the equation is the cost. Acquisition cost for a robotic pavement crack sealer is expected to be $100,000 with an expected life of 6 years. During this time, a crack sealing system might be used for 6 months of the year by 4 crews. The operation and maintenance of the system is $10,000 per year. Assuming a discount rate of 5% the total annualized cost for the system is $7,400 per crew per year. It is expected that 27 states will adopt the system. These states have approximately 1800 crews which would use 450 crack sealing units. Therefore, the net operating benefits represent $5.2 M per year.

Another benefit from an automated crack sealing system is improved quality. Generally, the best manual work will equal or exceed the performance of automated operations. Nevertheless, worker fatigue, inattention or skill variation can result in average work performance which is inferior to automated operations. Improved quality can result in reduced maintenance and construction demands in the future as well as improved roadway surface performance. Safety will also be improved with an automated system. By substituting robotic systems for manual work in the field, the exposure of workers in unsafe roadway conditions is greatly reduced. In addition to exposure to uncontrolled vehicular traffic, roadway workers applying crack sealing material are exposed to organic volatiles that can cause respiratory problems[2]. In summary, a robotic crack sealing system can have significant and substantial economic benefits.

3. DESIGN AND CONFIGURATION OF THE ROBOTIC CRACK SEALER

Crack sealing is normally conducted by a five to nine person road crew[3]. The equipment used includes pylons, a heavy truck, a tank of sealant, a heated air torch, a sealing wand, and a routing machine if the cracks are being routed prior to being sealed. One or two crew members may be necessary to direct traffic and place pylons. If the cracks are being routed, the router precedes the truck. An operator walking behind the truck blows out the cracks with the torch, and another follows with sealing material. A sand covering may be applied to permit immediate use by traffic. The procedure varies significantly from region to region[4] (Figure 1). For example, the Ontario Ministry of Transportation uses an equipment train with two routers to balance workloads[5].

There are a variety of functional approaches that can be considered for automated crack sealing. Alternatives may have varying degrees of manual supervision. Use of individual effectors for blowing and sealing requires that each will somehow be drawn precisely along the length of the cracks to be sealed. A manipulator is necessary to control the path of the individual effectors. Options include:(a) having the truck driver tele-operate the manipulator while the truck is stopped, (b) having the truck driver check or add crack location input to a partially automated system in which the manipulator would be controlled automatically, and (c) and having the operator simply monitor with interrupt control a largely autonomous crack sealing operation. To minimize driver distraction and to ensure future flexibility, the last option has been pursued.

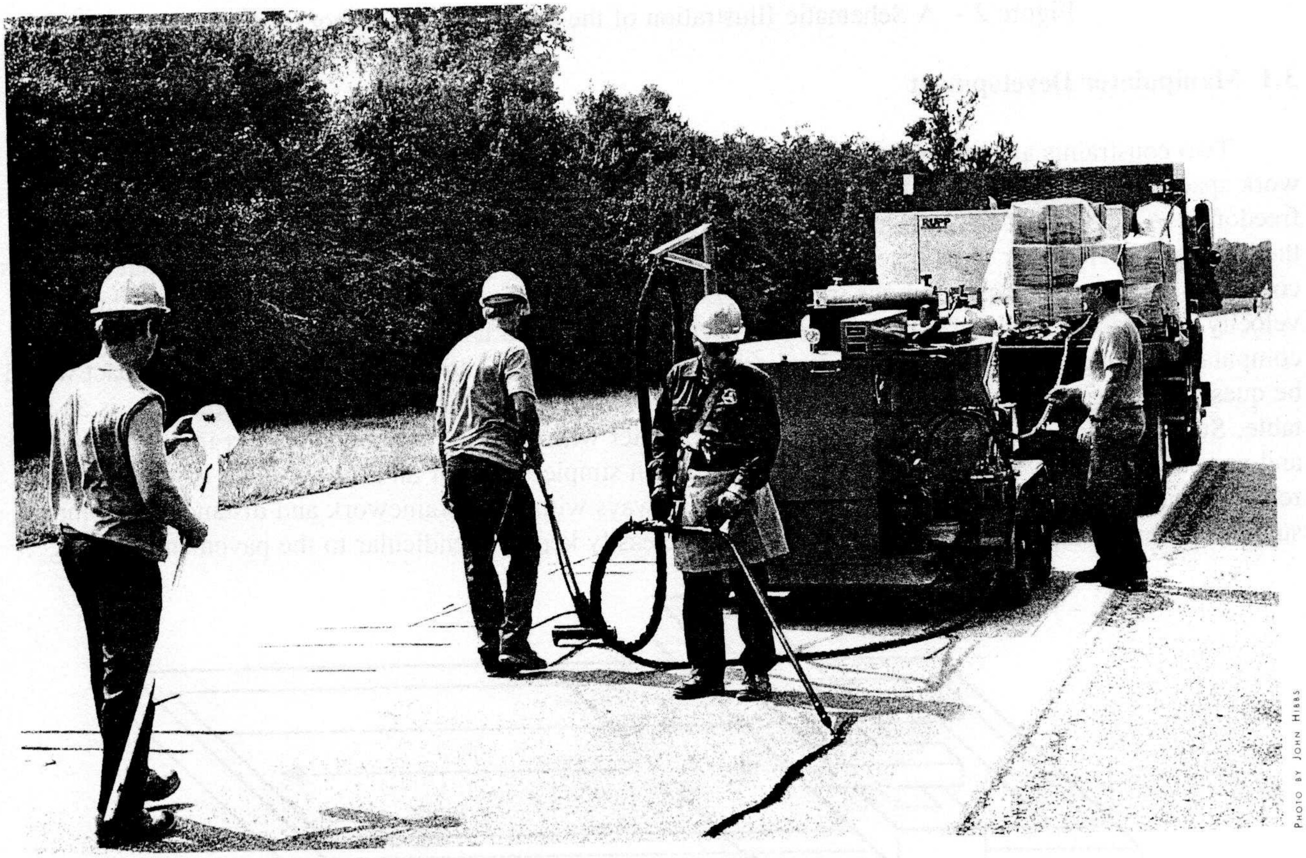
PHOTO BY JOHN HIBBS

CRACK SEALING AT A TEST SITE ON ROUTE 90

NEAR OCEAN CITY, MARYLAND.

Figure 1 - Crack Sealing Crew
(photo taken from "NRC Strategic Highway Research Program 1991 Annual Report")

A schematic illustration of the conceptual system design appears in Figure 2. A lead vehicle would tow a manipulator assembly and the grout and propane tanks. The lead vehicle would carry the power source for the manipulator and the necessary computing equipment. A camera would be mounted on an extendable boom so that it can be suspended above the work surface during operation. A video monitor would be located next to the driver for monitoring and over-ride. Three tools would be mounted on the manipulator. They include the heated air torch, the grout wand, and an infrared laser range sensor. (The range sensor and camera are used for automated crack detection.) The robotic pavement crack sealing system described here is an initial field prototype of this design which implements all of the system's key functions.

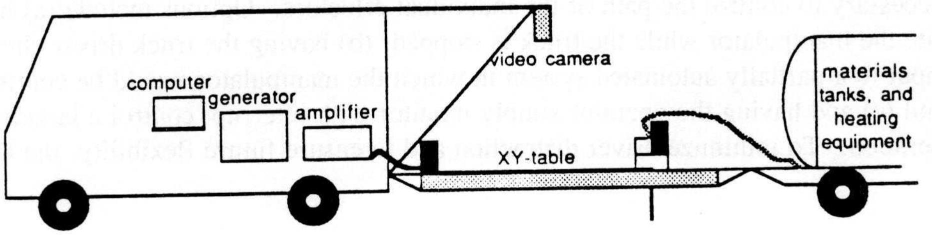

Figure 2 - A Schematic Illustration of the Crack Sealing Robot System

3.1 Manipulator Development

Two constraints are imposed on the manipulator. All parts of the manipulator must remain within the work space defined by a section of the pavement, and the manipulator must have at least two degrees of freedom. A device that first suggests itself as a manipulator is a robot arm cantilevered out from behind the lead truck. However most cracks describe irregular paths. Following such paths requires that the arm's controller calculate control solutions in real time for complex paths while also maintaining a constant velocity. Heuristics might also be required to keep the arm within its work space. As a result, computational requirements for arm control are severe. In addition, an arm's resistance to an impact would be questionable given the potential moments about its joints. A simpler solution for manipulation is an xy-table. Such a device works much like a large scale plotter with a gantry and mounted cart implementing x and y motions respectively (Figure 3). Control is much simpler than for an arm. A table is more impact resistant and stable than an arm, since reactions are always within the framework and distances to points of support are minimized. In addition, the effectors are easily kept perpendicular to the pavement surface.

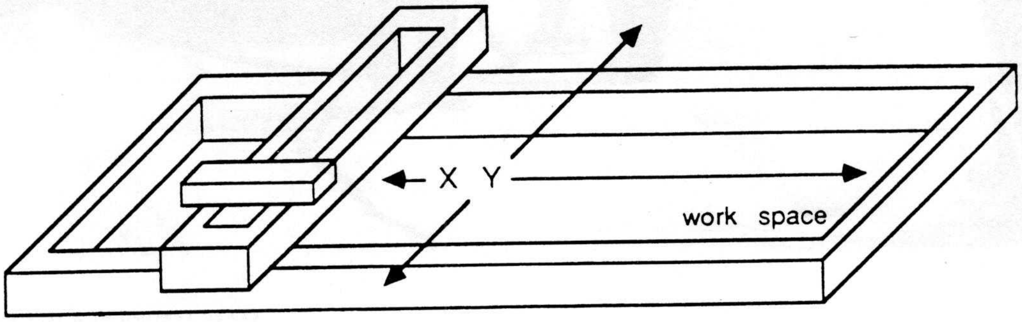

Figure 3 - Table Conceptual Design

A robust and transportable field prototype xy-table was constructed in the second phase of the project (Figure 4). The dimensions of the frame are approximately 5 x 10 ft. It includes a subframe, a camera superstructure, and a manipulator support frame. The subframe is made of welded steel, is drawn on 4 rubber tired double wheels, and has a trailer hitch attached. The support frame supports the gantry which transverses the longer dimension. Rubber isolation between the subframe and support frame isolates the range sensor and effectors from the wheeled subframe. The gantry in turn supports a cart which moves in the shorter dimension. Two cameras are mounted about 8 feet above the ground on a support attached to the frame and the range sensor is mounted on the cart. The support frame, cart, and gantry are constructed of anodized tubular aluminum. Power and material lines are attached to the manipulator where they will least interfere. The xy-table can be dismantled and transported in a small cube van, then assembed on site and towed behind the lead truck. For field assembly, the gantry is easily lifted by two men and placed on the framework. The cart is then lifted and placed on the gantry. The drive system is comprised of rack and pinion transmissions for the gantry and cart driven by two stationary servo-motors which are powered by a single axis motor controller box for each motor. All control and sensor data processing is executed on a PC. Further development is required for a commercial system. For example, a production system's dimensions would have to extend across a full lane width.

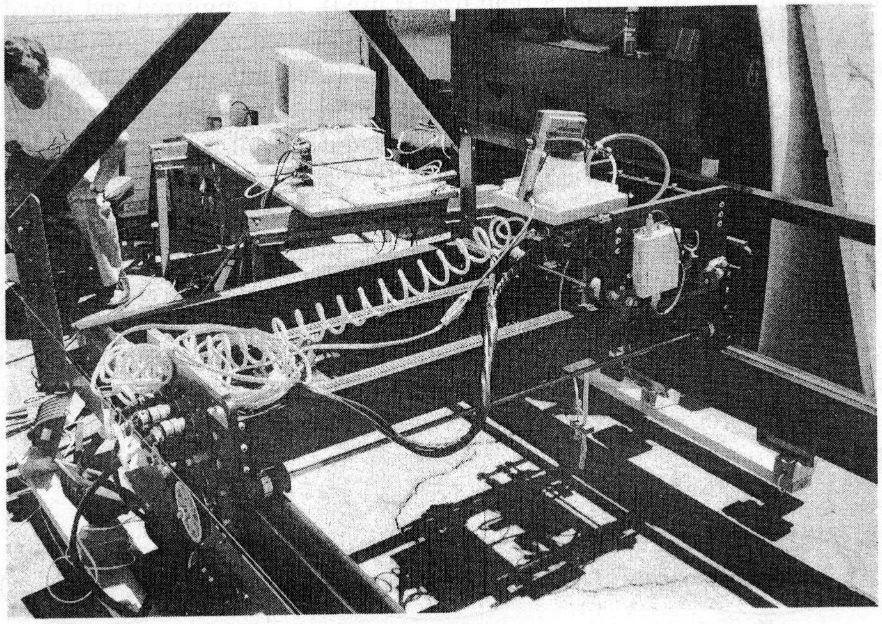

Figure 4 - Field Prototype xy-Table

In the following sections, requirements for automating the "actions" of the crew members who blow and fill the cracks are described. The crews' actions include identifying the cracks to be sealed and then, in effect, tracing the cracks with the torch and the wand.

3.2 Crack Detection and Mapping

Identifying cracks in the road surface automatically is not an easy problem[6,7,8] . Mapping the layout of the cracks in detail and selecting those to be sealed increases the difficulty. Only in the case of routed cracks is the problem simplified by distinct visual patterns of debris and by consistent groove dimensions. To identify routed or unrouted cracks, characteristic surface data is required.

Video cameras can acquire a raster pattern of digitized surface grey level values very efficiently. Even with good data however, a vision system can be fooled. Analysis of a video image alone shows that it is almost impossible to automatically detect the difference between a routed crack, a sealed crack, and a strip of dark oil. With the corroboration of range information however, the routed crack can be distinguished from the imposters. The infrared laser range sensor attached to the manipulator (described earlier) can acquire range information in virtually any sampling pattern within the manipulator's work envelope. In practice, both range and vision sensors experience noise because of the varied topological, color, texture, and lighting conditions of the pavement surface.

Combining information from multiple sources in a common surface representation can therefore increase the accuracy of crack perception. The facilities required to do this exist in a general pavement surfaces model[9]. The model is a combination of a surface representation and the process of deriving it. The representation is composed primarily of two data structures, a grid, which supports sensor data structuring and early fusion processes, and a multi-layer surface quadtree, which is used to spatially relate properties and features in a framework useful for feature extraction and for applications. The multi-layer quadtree makes it possible to combine sensor information at various levels of abstraction and aggregation.

In the automatic crack detection and mapping process (Figure 5) a video image of the work area is acquired first (In this description, data from a field trial is used). It is digitized and stored in computer memory as a 512 x 512 array of pixels. The image is then segmented using a grey level thresholding operation which is manually tuned (Figure 6a). More sophisticated and autonomous segmentation procedures are unnecessary because of the slow moving equipment train and the availability of the driver for tuning. The image is divided into cells of 8 x 8 pixels and each cell is classified as occupied or unoccupied by what looks like a crack. The result is a cell occupancy array of 64 x 64 cells. The cell occupancy array is then filtered to remove stray cells. Clumped strings of cells correspond to cracks on the road. These clumps are thinned into singly connected strings of cells using a skeletonizing algorithm, so that the strings can be converted into an ordered set of work area coordinates that can be used to generate instructions for the manipulator (Figure 6b). The occupancy array is then converted to the multi-layer quadtree data structure. The strings are identified as connected groups of cells using a connected component labeling algorithm, and very small strings are removed automatically (Figure 6c). The remaining strings may still represent marks or filled cracks, so range information is required to corroborate or dismiss each string.

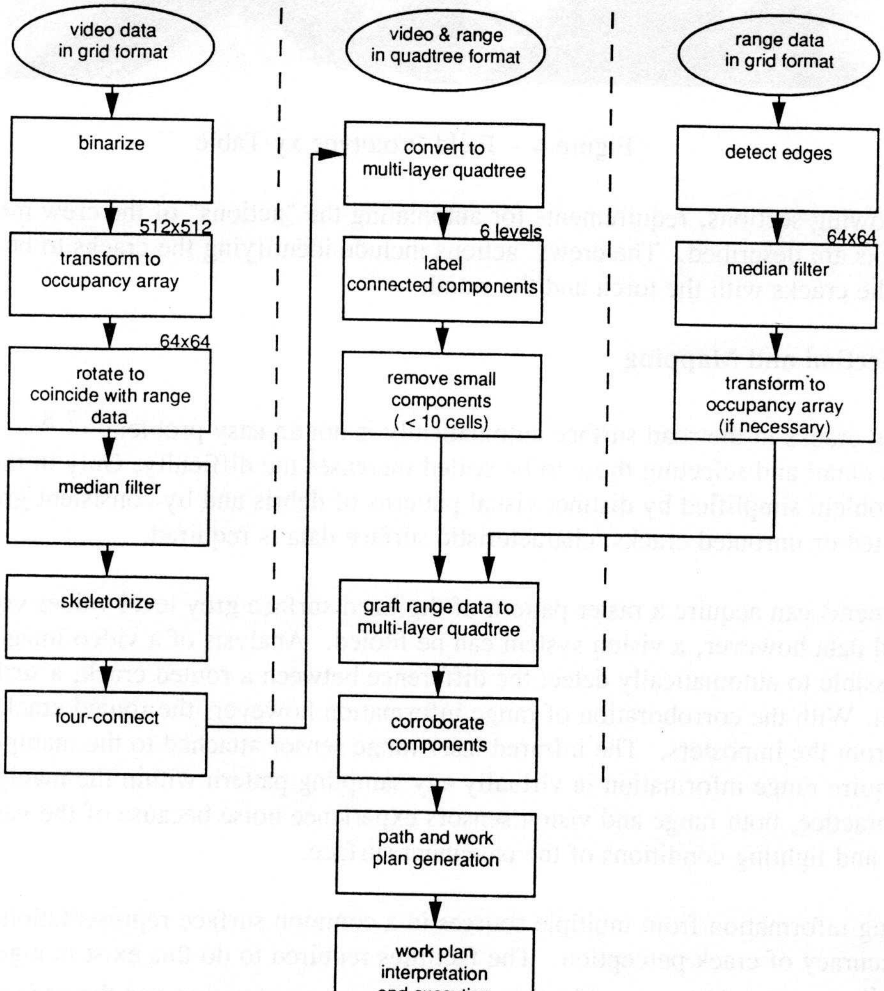

Figure 5 - Crack Detection and Mapping Process

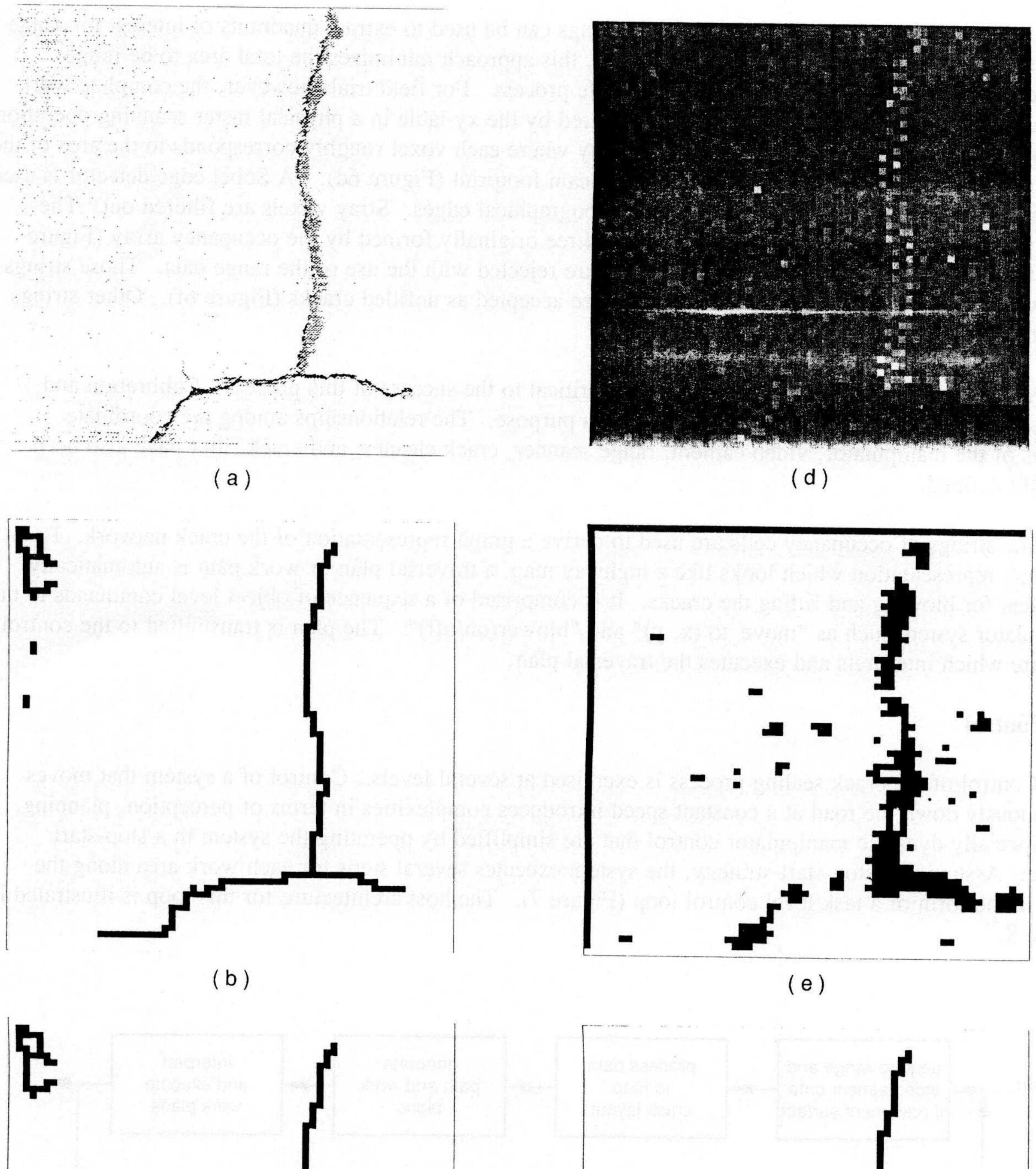

Figure 6 - Interim Detection and Mapping Data for Field Trial 1.1

The occupancy array with the remaining strings can be used to extract quadrants of interest for range scanning. Since range scanning is relatively slow, this approach minimizes the total area to be range scanned and lowers the time required for the whole process. For field trials however, the complete work area has been range scanned. Range data is acquired by the xy-table in a physical raster scanning operation. The range data is acquired in a 64 x 64 voxel array where each voxel roughly corresponds to the area of the work surface illuminated by the range scanner's beam footprint (Figure 6d). A Sobel edge detector is used to segment the range image, since cracks form topographical edges. Stray voxels are filtered out. The resulting array is merged into the multi-layer quadtree originally formed by the occupancy array (Figure 6e). Strings that would have mislead the system are rejected with the use of the range data. Those strings with range data overlapping their occupied cells are accepted as unfilled cracks (Figure 6f). Other strings are rejected.

Alignment of the range and vision scans is critical to the success of this process. Calibration and alignment techniques have been developed for this purpose. The relationships among the coordinate systems of the manipulator, video camera, range scanner, crack cleaner, and crack filler have also been carefully defined.

The strings of occupancy cells are used to derive a graph representation of the crack network. From the graph representation which looks like a highway map, a traversal plan or work path is automatically generated for blowing and filling the cracks. It is comprised of a sequence of object level commands to the manipulator system such as "move_to (x, y)" and "blower(on/off)". The plan is transmitted to the control software which interprets and executes the traversal plan.

3.3 Control

Control of the crack sealing process is exercised at several levels. Control of a system that moves continuously down the road at a constant speed introduces complexities in terms of perception, planning, and especially dynamic manipulator control that are simplified by operating the system in a stop-start manner. Assuming a stop-start strategy, the system executes several steps for each work area along the road, in the form of a task level control loop (Figure 7). The host architecture for this loop is illustrated in Figure 8.

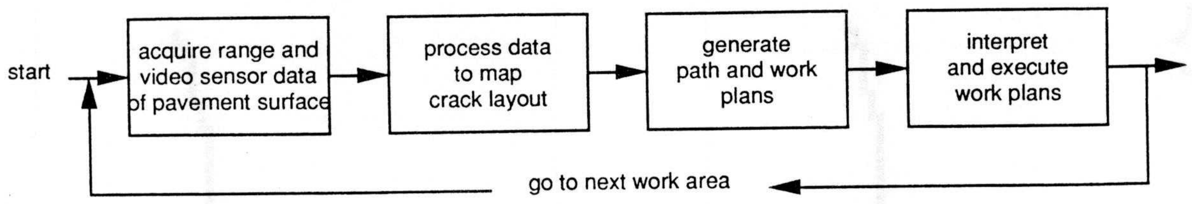

Figure 7 - Task Level Control Loop

The object level commands in the work plan result in machine level control problems that are more or less complex depending on the equipment configuration. In the case of an xy-table a command to move from point (x1,y1) to (x2,y2) can be translated directly to a number of revolutions for each one of an X and Y drive motor. Servo-control motors allow additional control of acceleration and velocity. Additional, higher level feedback may also be required for confirming progress and accuracy of the mechanisms and for registering changes in position of the table with respect to the pavement surface. Visual images may be sufficient for this purpose.

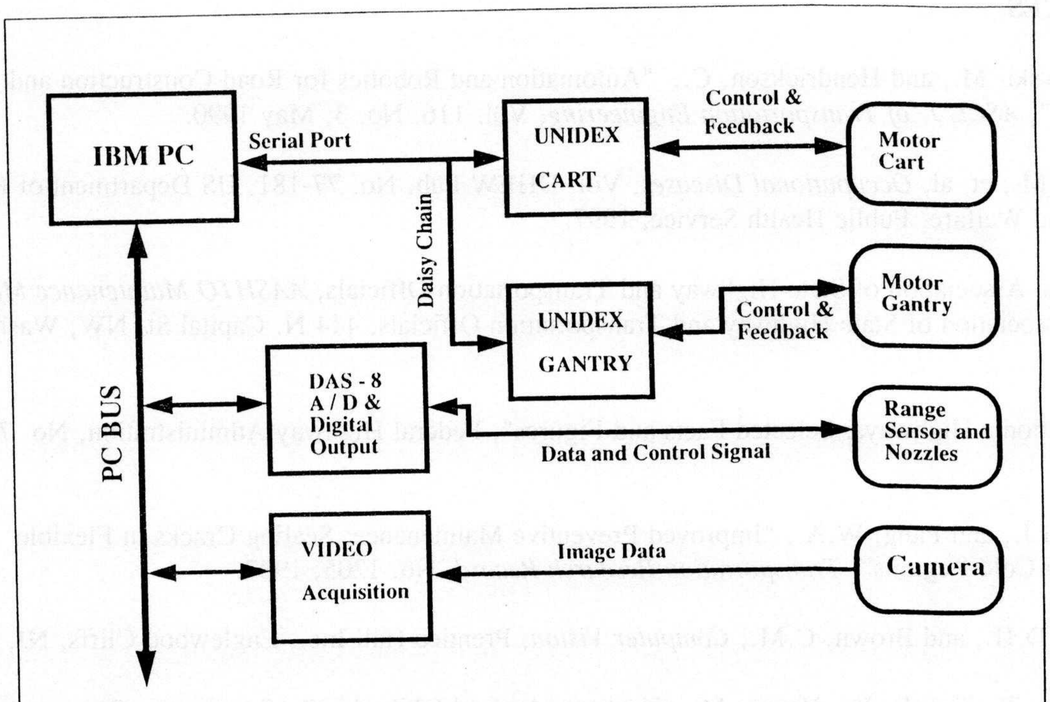

Figure 8 - XY-Table Control Schematic

4. CONCLUSIONS

An automated crack sealing system can have substantial economic benefits. These benefits are accrued through reduced labour costs, improved quality, and improved safety. Technological advances such as new sensors, faster computers, better sensor interpretation algorithms, and more flexible manipulator hardware have made automation of crack sealing feasible. In particular, the blowing and sealing operations are most amenable to automation.

A fully automated crack sealing system requires a manipulator, sensors, effectors, computerized crack detection, pavement surface modeling, and equipment control. In the system design described here an xy-table is used as a manipulator because of its stability, impact resistance, and simplified control requirements. A pavement surface model combines vision and range sensor data for crack detection and mapping. A field prototype has been constructed to demonstrate and test the system design, and to conduct experiments in sensing and tracking sequences. The prototype design has proven feasible.

The technical problems to be overcome in a field hardened production system are still substantial. While the occupancy cell approach has reduced crack detection processing time, making it realistic to use a PC for both control and crack detection, real time video imaging, feature extraction, surface representation, motion planning, and robot control must still be achieved. Integration of perception, planning and control is particularly challenging. Fortunately, existing technology can be tapped for many of the required improvements.

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