도로면 유지보수를 위한 크랙실링 자동화 로봇의 개발과 응용
-현장적용을 통한 실험결과 분석을 중심으로-

Technical Advances in Robotic Pavement Crack Sealing Machines and Lessons Learned from the Field

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Abstract

Crack sealing, a routine and necessary part of pavement maintenance, is a dangerous, costly, and labor-intensive operation. Within the North America, about $200 million is spent annually on crack sealing, with the Texas Department of Transportation (TxDOT) spending about $7 million annually (labor alone accounts for over 50 percent of these costs). Prompted by concerns of safety and cost, the University of Texas at Austin, in cooperation with TxDOT and the Federal Highway Administration (FHWA) has developed a unique computer-guided Automated Road Maintenance Machine (ARMM) for pavement crack sealing. In 1999, successful field tests have been undertaken in 8 States around the U.S. This paper first describes significance of the automated crack sealing and technical advances in automated crack sealers including the ARMM, developed in the U.S. It then discusses the ARMM's field implementation and performance evaluation results, and improvements and modifications suggested through the technology evaluation during the field trials. Current research efforts and future work plans in its further development are also presented in this paper.

Keywords : Construction Automation, Pavement, Crack sealing, Maintenance Robot, Pavement, Economic Feasibility Productivity

1. Introduction

Crack sealing, a maintenance operation undertaken by all state departments of transportation in the U.S., is dangerous, costly, and labor-intensive. In pursuing these operations, agencies must contend not only with the substantial personnel turnover and training problems associated with crack sealing, but also with the traffic disruptions that crack sealing operations typically generate. Automation of pavement crack sealing is of considerable interest for several reasons. First, robotic crack sealing would improve safety by minimizing the exposure of maintenance workers in unsafe working conditions, which may involve extremes of traffic volumes, temperature, wind, and debris. Such adverse environmental conditions can significantly lower quality and productivity of the sealing crews as well. Second, it can have significant economic benefits. For example, approximately $200 million is spent annually on pavement crack sealing in North America. About 25% is privately contracted, labor costs average between 50% and 60% of total crack sealing costs. It is currently estimated that the UT Automated Road Maintenance Machine(ARMM) would have a purchase cost of approximately $100,000, a useful life of 5 years, $10,000 annual maintenance costs, and $100,000 in annual cost savings by eliminating three laborers. A very high rate of return (ROR) results. According to the most recent economic analysis, if ARMMs were implemented throughout Texas, the direct savings are estimated to be $2.43 million for TxDOT (at 4% MARR) and $2.64 million for the private contractors (at 20% MARR) over a 6 year planning horizon. The road user-cost savings are also estimated to be $11 million for the 5196 kilometers of the interstate highways in the State of Texas. Total user-cost savings would be much higher since the savings on urban freeways and streets, farm-to-market roads, and

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secondary roads are not included in this $11 million estimate. Over a 30 year planning horizon and from a national perspective, the net present worth of automated crack sealing could be in the hundreds of millions of dollars.

This paper first discusses technical advances in automated crack sealers developed in the U.S. Then, it mainly focuses on describing the results of the ARMM's field demonstration conducted in 8 States around the U.S. during summer 1999 and its performance evaluation, and comments and suggestions obtained from the technology evaluation during the field trials. Finally, conclusions and recommendations are made concerning the value of implementing the automated pavement crack sealing and its application areas. Current research plans for examining the applicability of a robotic crack sealing technology in Korea are also briefly introduced in the paper.

2. Technical Advances in Automated Crack Sealers

In recent years, several systems for automatically routing and sealing surface cracks have been developed in the highway construction and maintenance area (Haas 1996). Each system is chronologically described, and their key research issues and technical advances are identified in this paper. Visual appearances of each prototype system are illustrated as well.

2.1 CMU Laboratory Prototype [1990]

The automated crack sealing system was first visualized as an equipment train composed of equipment trailer, a manipulator, and a large van containing computer and power equipment. An xy-table manipulator was selected among some alternative manipulator options because of its ease of control and robust physical characteristics. A machine vision system was proposed for crack mapping in the automated crack sealing operation. The major design objective of the laboratory prototype was to demonstrate the feasibility of the conceptual design. At this stage, an xy-manipulator was assembled in the lab and pavement sections for tests were fabricated (Fig. 1). A video camera mounted above the work space was employed to acquire crack images which were digitized and then combined with laser range data of surface contours using a 'Multi-layer Quadtree' model and image analysis algorithms (Haas et al. 1990). However, the following problems were identified in the first phase of development: (1) Unacceptably slow speed; the system required 20 to 30 minutes to complete the scanning, mapping, and work process cycle, and (2) Hard to calibrate the sensing and manipulator subsystems because of the hasty assembly of the prototype. Some solutions were proposed for the development of a field prototype.

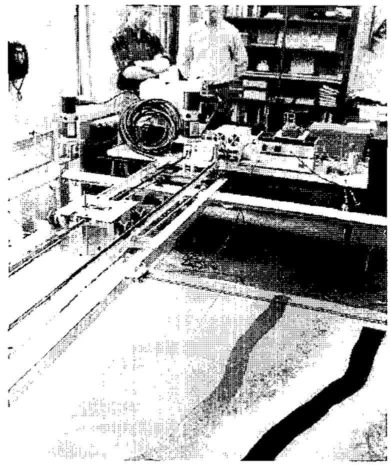


Fig. 1. CMU Laboratory Prototype

2.2 CMU-UT Field Prototype [1992]

Consolidation of control and data processing were accomplished on a single Intel 386 PC. Operation on unrouted cracks was performed in a parking lot. A more robust xy-manipulator was fabricated for ease of control and stability of operation(Fig. 2). The demonstration of this CMU-UT prototype was successful but the system was retarded by still slow range scanning speed (Haas et al. 1992).

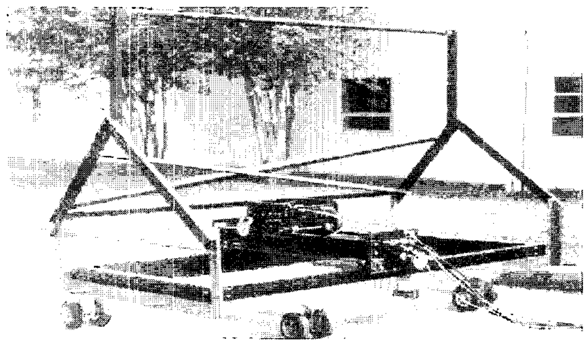


Fig. 2. CMU-UT Field Prototype

2.3 CalDavis Field Prototype [1993]

The University of California at Davis developed a field prototype of an automated crack sealer in a subsequent and related development effort. The final prototype of this crack sealing machine employed multiple manipulator arms, which could prepare and seal longitudinal joints at 16 kilometers per hour (Fig. 3). A 'Histogram-Based Machine Vision Algorithm' was utilized to automatically detect the position and orientation of roadway cracks to be sealed, but the crack recognition algorithm still had a problem in accurately sensing cracks to be sealed. A simple traversal plan was also developed to determine the order in which cracks are sealed. The demonstration was successful but the expensive selling price of the machine, US $550,000, failed to attract private contractors or government departments. Thus, development efforts of this machine halted (Velinsky 1993).

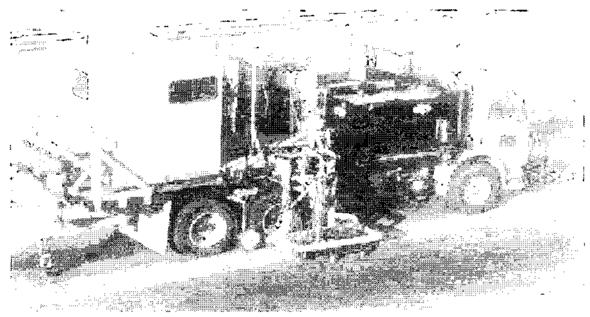


Fig. 3. CalDavis field Prototype

2.4 UT Field Prototype [1995]

The UT field prototype (Fig. 4) employed a remote and graphical control system. The system combined machine vision and operator input via a mouse to map the exact location of roadway cracks to be sealed. Machine vision software in order to detect the cracks to be sealed and center the manually drawn lines along the crack spines using a local search algorithm was examined during this project period. Also, a path planning software for efficiently traversing crack networks to be sealed was developed. In a set of experiments, implicit path planning was compared with automated path planning.

However, incorporation of this machine vision software was postponed to the next phase, the development of a commercial prototype (UT Automated Road Maintenance Machine). Also, it was realized that the data structures of the path planning software developed could be more simplified by eliminating the graph conversion process, thus minimizing overall process loop time of the crack sealing robot.

Fig. 4. UT Field Prototype

2.5 UT Automated Road Maintenance Machine (ARMM) [1997~Current]

A man-machine balanced Automated Road Maintenance Machine for automatically sealing pavement cracks has been developed, tested, and successfully demonstrated by the University of Texas at Austin, in cooperation with TxDOT, the FHWA, and Crafco, Inc. (Fig. 5). It has taken several years for the UT ARMM to achieve an optimal balance between human and machine functions for automated pavement crack sealing. The tradeoffs between various levels of automation for specific functions required to control the ARMM have been experimented. Even if the ARMM is an upgraded version of the UT field prototype, there have been significant changes in software and hardware of the system.

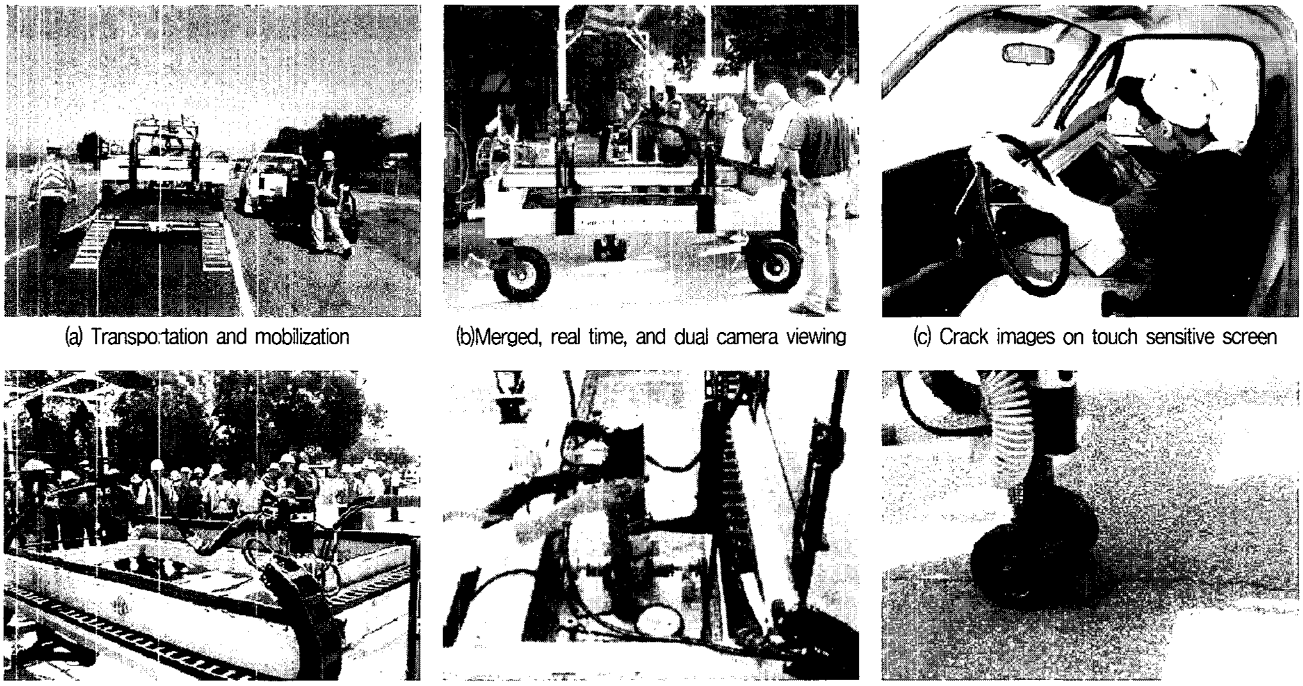
The ARMM uses an xy-manipulator with a rotating turret to blow, seal, and squeegee cracks in one pass, thus greatly improving productivity of the system. While the manipulator is moving within its work area, its frame is stationary. Sealing cracks in one work area and then moving to the next work area is considered one work cycle. To control the ARMM through a work cycle, five steps are required including: (1) image acquisition, (2) manual crack mapping and representation, (3) automated line snapping and manual line editing, (4) automated path planning, and (5) manipulator and end effector control. A detailed description of this man-machine balanced crack sealing process was described elsewhere (Kim et al. 1998, Kim 1998).

The ARMM, which costs approximately $125,000, may ultimately be able to seal cracks up to about three times faster than conventional methods and can eliminate about three workers from a sealing crew. Parts for the system developed at The University of Texas at Austin are mostly off-the-shelf and total approximately $70,000. Additional costs for assembly, marketing and profit will require a sale price up to $125,000. Since approximately 3~4 laborers will be eliminated, it is estimated that the payback should be approximately two years. Compared with the previous prototype systems, key technical advances implemented in the ARMM would include:

1) Achievement of an optimal man-machine balance
2) Merged, real time, dual camera viewing
3) Simplified graphical control buttons, and variable speeds for cracks of variable widths (Fig. 6)
4) Computer controlled electronic switch for the sealant wand
5) Motion control modifications
6) Larger motors

3. Field Implementation of the ARMM

In 1997 and 1998, the ARMM's first field demonstrations were



(a) Transportation and mobilization (b)Merged, real time, and dual camera viewing (c) Crack images on touch sensitive screen

(d) ARMM in demonstration (e) ARMM's cart, gantry, and motors (f) ARMM's end-effector

Fig. 5. The UT Automated Road Maintenance Machine

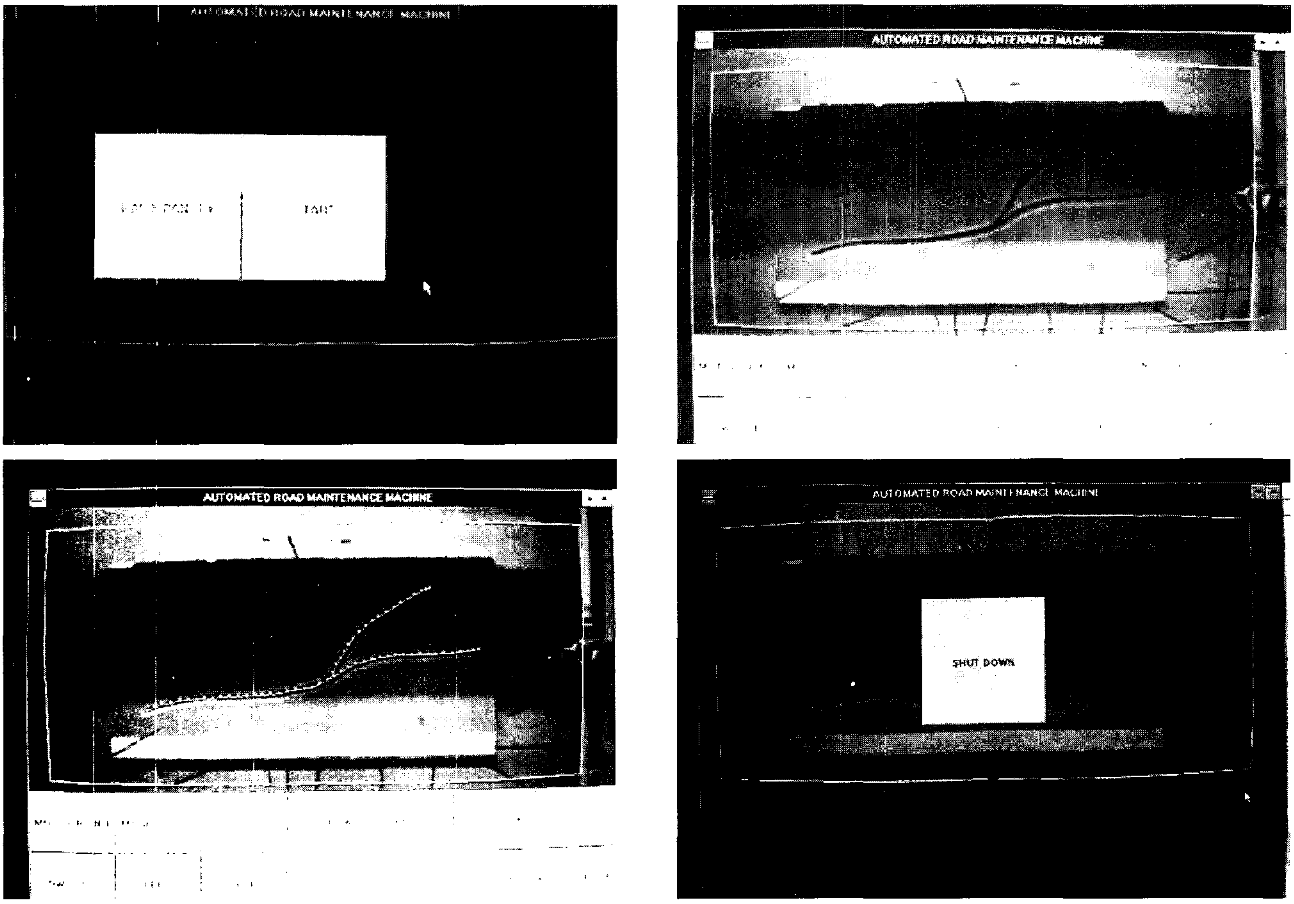


Fig. 6. Graphical User Interface(GUI) of the ARMM's Vison Software

performed at five locations in the State of Texas (Austin, San Antonio, Dallas, Corpus Christi, Travis County) with encouraging results. During summer 1999, the ARMM's second field trials with a full-scale crack sealing units were conducted at 9 cities in 8 States (AZ, CA, UA, CO, WY, ND, OK, MO) around the U.S. (Table 1). This schedule for the ARMM's field demonstrations was organized

Table 1. Schedule of the ARMM's Field Trials in 1999

City	Date	Location	Demo Time
Oklahoma City, Ok	99/6/02	US-66 & HW-92	09:00 am~
Kansas City, MO	99/6/07	IH-80	12:00 pm~
Bismarck, ND	99/6/10	Bismarck Zoo	09:00 am~
Casper, WY	99/6/16	IH-25	09:00 am~
Denver, CO	99/6/21	CoDOT Headquater	09:00 am~
Salt Lake City, UT	99/6/29	UT-DOT HQ	10:00 am~
Truckee, CA	99/7/01	IH-80	07:30 am~
Tucson, AZ	99/7/07	IH-10	10:30 am~
Crafco, AZ	99/7/09	Crafco Inc., Headquarter	10:00 am~

through the ASCE, NCHRP, AASHTO, and WASHTO meetings, along with state highway departments' research meetings. The dates and locations were selected so that the tour could follow a circular path starting out North from Austin and returning to Austin from the West after stopping in each of the 9 cities listed in Table 1. The tour was scheduled to visit each department of transportation (DOT) of 8 different States over a six week period between May 31, 1999 and July 16, 1999. Table 1 shows the schedule, which the tour followed with the various locations where the field demonstrations took place.

Objectives of these field demonstrations were to:

1) gain additional field experience
2) acquaint maintenance personnel around the country to the potential of the automated crack sealing technology
3) acquire more feedback from maintenance personnel, for well designing a subsequent commercial model
4) collect additional productivity data
5) perform further proof testing the equipment under real working conditions
6) acquire additional video footage

During the ARMM's field trials, evaluation of the crack sealing technology was based on: 1) field trial experiences, 2) observations by maintenance personnel, 3) key vendor input, and 4) detailed productivity analysis. Evaluations were submitted by maintenance personnel, vendors and key administrators, and they were then analyzed. Initial productivity analysis results (3.1 lane-kilometers/day) also indicated that the economics of the current prototype are beginning to be competitive with conventional method (Table 3), while only minor changes are required to significantly improve the machine's advantages. From the field trials, it was also identified and validated that numerous additional benefits are associated with the crack sealing technology over the conventional method. Those would include:

1) Greater accuracy.
2) Less wastage of materials is expected, because of the application method and because video documentation of all operations is possible. Reduced waste of rubberized asphalt sealant material is an environmental benefit.
3) Measurement of the total exact length of cracks filled. Images of work performed can also be automatically recorded.
4) The sealer can significantly increase the ARMM's productivity since it can work at night. Benefits to vehicular traffic are also expected.
5) Safety is improved significantly by removing three laborers from hazardous roadwork. Interference with traffic should be minimized as well.
6) Functionality of the machine can be extended with minor modifications to routing, cutting for loop detectors, refinishing, specialized pavement markings, joint sealing, pothole filling, and other tasks.

Other lessons learned from the field trials were:

1) Expeditions can be extreme
2) Impediments to technological innovation similar to those in construction
3) Reactions vary widely

4. Performance Evaluation of the ARMM

4.1 ARMM's Productivity

The main objective of the productivity study was to examine if the ARMM can meet the productivity of standard crack sealing crews and rate the overall performance of the ARMM according to the severity and types of cracking. A mathematical model (Kim et al. 1997; Table 2) which predicts the productivity of the ARMM was developed as a means of rating the performance of the ARMM. In the equation, the tasks associated with the ARMM's operation were divided into five major components to rate its overall performance. Those include: 1) mobilization, 2) crack detection, manual crack mapping, automated line snapping, and manual line editing, 3) crack sealing, 4) move to the next workspace (transition of the workspace), 5) demobilization. Each component was then classified into its subtasks. In the model, the time for path plan was eliminated because it can be done in a fraction of second by the computer (Kim et al. 1998). Data for the productivity analysis were collected from the recent field trials conducted at 9 cities in 8 States around the U.S. Distress types of pavement sections for the productivity study were divided into four major categories

Table 2. Productivity Model for Performance Evaluation of the ARMM

ARMM's Productivity Model
Total length of sealed pavement / [Time to mobilize + Total time to trace, line snap + Total time to blow, seal, and squeegee + Total time to move the ARMM + Time to demobilize] = Productivity of the ARMM (lane-kilometer/hour)

Table 3 Productivity Comparison of Automated Method and Conventional Method

Comparison of Overall Daily Productivity	
Automated Method by ARMM	Conventional Method
3.1 lane-kilometers/day (1997)	3.2 lane-kilometers/day (Malek 1993)
3.7 lane-kilometers/day (1999)	

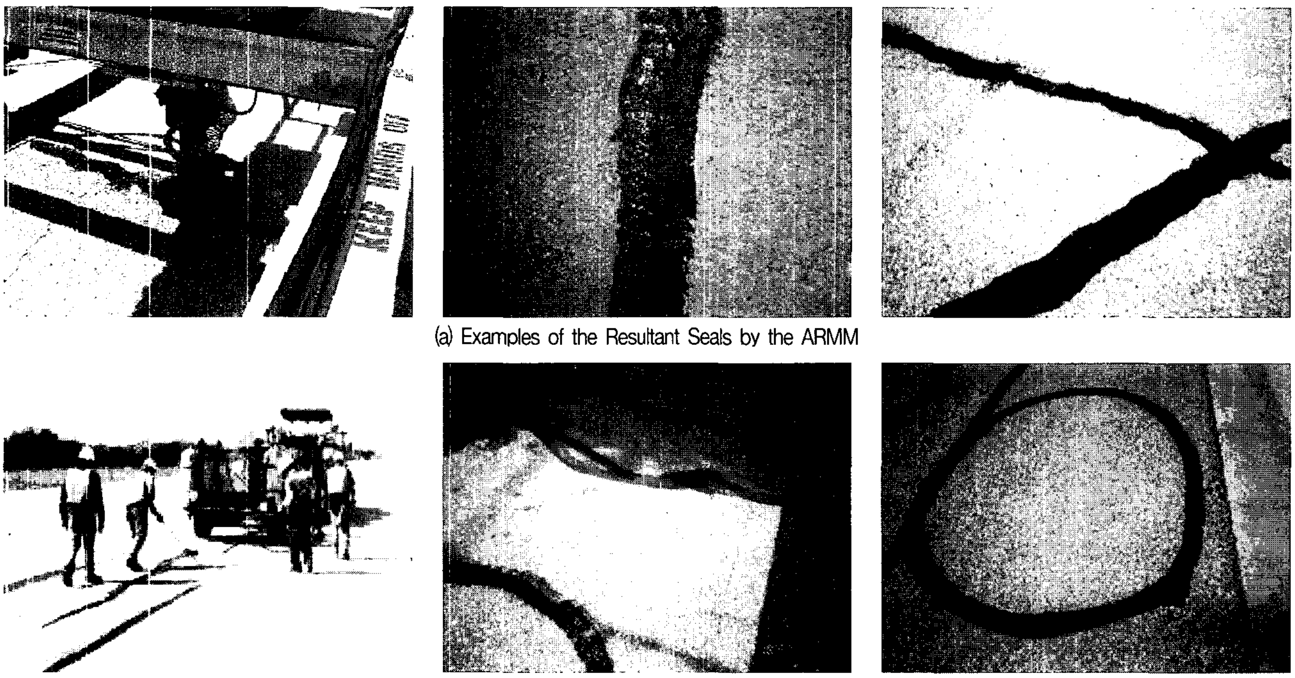
including: 1) longitudinal cracking, 2) transverse cracking, 3) block cracking, and 4) joints. Alligator cracking was not sampled because other surface crack maintenance options such as 'patches' or 'overlays' would be preferred to repair the alligator cracking, instead of the 'routing and sealing' method.

Table 3 shows the most recent ARMM's productivity analysis result, performed in the UT Field Systems and Construction Automation Laboratory (FSCAL). The result could surpass the ARMM's initial productivity analysis result, based its first field trials because of the recent improvements in its hardware (purchase of faster processor and LCD touch panel screen with stylus, and modification of support arm for sealant hose) and software (some modifications of its vision software). In the initial productivity analysis result indicated that the ARMM was competitive with conventional methods, but had greater accuracy, less waste, less labor cost, and the measurement of the total exact length of cracks filled (which also provides the amount of sealant used).

However, the ARMM's achievable productivity rate should be several times those calculated in Table 3, by employing several improvements (Table 4) suggested from the DOT representatives, maintenance personnel, and sealing crews during the recent ARMM's field trials. For example, the ARMM with the ability to work at night with the mounting of lights on its canopy would almost double the current daily productivity rate. When regarding these elements, achievable productivity rate of the ARMM should be several times that to be presented, thus making the automated crack sealing more favorable. Also, in the current prototype system, the crews are spending much time on mobilizing (20 minutes) and demobilizing (15 minutes) the ARMM. In the long run, the ARMM would be built as a single unit. In this case, times for mobilization and demobilization will be negligible and should be removed from the productivity model. This will also significantly improve the overall productivity of the ARMM.

4.2 Quality in Resultant Seal

In this study, a quality comparison between the automated crack sealing method and conventional method could not yet performed, due to the lack of samples in resultant seal by the ARMM. Additional collection of quality data would be required for benchmark comparisons in the near future. However, it is expected



(a) Examples of the Resultant Seals by the ARMM

(b) Examples of the Resultant Seals by the Conventional Methods

Fig. 7. Resultant Seals by Automated and Conventional Methods

that the automated pavement crack sealing (Fig. 7-(a)) can achieve improved quality over existing field operations (Fig. 7-(b)). In general, 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. Also, the pavement crack sealing procedure is not standardized and there is a large distribution (Fig. 7-(b)) in the quality of the resultant seal (Haas et al. 1992). Moreover, crack sealing can be performed under field conditions, which may involve extremes of temperature, wind and debris. Such adverse environmental conditions can significantly lower both quality and productivity of the sealing crews threatening their safety. Improved quality also can result in reduced maintenance demands in the future by improved pavement surface performance. Fig. 7 shows several examples of the resultant seals by both methods.

5. Current Research Efforts and Future Plan

Lists of common comments and suggestions from the DOT representatives, maintenance personnel, sealing crews during the field trials are shown in Table 4. It also shows the improvements which are currently being considered and to be modified in the near future.

Table 4. Improvements and Modifications Suggested from the Field Trials

	Comments and Suggestions	Improvements being considered; to be modified
1	Eliminate need for turret to return to its home position after each crack	V
2	Have emergency switches on the ARMM accessible to the workers around the robot	V
3	Install lights for night-time operation	V
4	Change the shape of the squeegee to a circular design which can contain the sealant; change the shape of the squeegee to a "V" or "U" shape	V
5	Develop a retractable turret, which can maintain a constant height off the ground and eliminate the wheels	V
6	Implement a telescoping frame design which can be adjusted to different widths depending on requirements	
7	Redesign the ARMM so that it can be towable without the need for a trailer	V
8	Mobilization and demobilization are too slow	V
9	Include all the equipment in one self-contained unit	V
10	Ergonomically design the tow vehicle's cab, and add better tinting, or mini-blinds to reduce glare on monitor	V
11	Need to make it work faster; it could work faster with the fabrication of lighter x-y manipulator (i.e. Replacing bearings, gantry, and motors would triple end-effector's speed) and use of larger motors	V
12	Consider using multiple air nozzles, which can cover an entire lane width in one go and possibly install a second one which will clean up after the first pass	

Since the ARMM performs well in its current configuration, current research efforts are mainly focused on conducting an in-depth design analysis of the ARMM in preparation of possible fabrication of future commercial models based on the improvements of the machine, and establishing its business strategy for procurement. As shown in Table 4, 12 comments and suggestions based on the evaluations varied in terms of the anticipated benefit/cost ratios. Finally, the most improvement elements in the comment and suggestions with high benefit/cost ratios were selected through brainstorming sessions between the UT research team and sponsors. Those 10 elements (Table 4) are currently being considered in the design process. Benchmark comparisons in sealing quality between automated method and conventional method would also be conducted in the near future. Also, feasibility studies and design analysis for examining the applicability of a more advanced robotic crack sealing machine applying machine vision and GPS/INS technologies, under Korea transportation environment are currently underway. The study mainly focuses on: 1) its needs analysis, and 2) its economic, financial, physical, and technical feasibility analyses. Detailed results of this study will be presented elsewhere (Sung et al. 2000).

6. Conclusions and Recommendations

Automating pavement crack sealing is of considerable interest for several reasons. It will improve productivity, quality and have safety benefits by getting workers off the road. In the case of the ARMM, the reduction in crew size and the increase in productivity of the sealing process will translate directly into significant potential savings in costs. Recent field trials of the full scale crack sealing units have indicated that automated pavement crack sealing is technically, economically, and financially feasible. The results of the ARMM's recent field trials conducted in 8 States in the U.S. were enough to support this conclusion. It is expected that its recent field demonstration results and media coverage would accelerate transfer of the automated crack sealing technology. A detailed design analysis of the ARMM in preparation of possible fabrication of future commercial model is currently being conducted at the UT FSCAL. Economic, physical, and technical feasibility of a more advanced automated crack sealer in transportation environment of Korea is also being analyzed. Finally, it is concluded that partial modifications of the algorithms and tools used in the ARMM would eventually have broader applications in automation of infrastructure maintenance. Applications areas would include: 1) real-time safety inspection in RC structures between construction site and home office, using multimedia and wireless data communication technologies, 2) acquisition of as-built drawings using representational forms (Kim et al. 1999), 3) tracking and modeling of deterioration or crack propagation, and 4) automated routing, message painting and marker placement.

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요 약

도로면 유지보수 공법 중 크랙실링은 그 특성상 작업수행과 관련하여, 노무자의 안전을 위협하는 다양한 위험, 열악한 작업환경으로 인한 생산성 및 품질저하, 교통체증으로 인한 차량이용자의 간접비용 상승 등 많은 잠재적 문제점을 내포하고 있을 뿐만 아니라 노무 의존도가 높고 년간 막대한 사업예산을 요하는 국가 기반 유지보수 사업이다. 선진 외국의 경우, 도로면의 초기균열에 대한 보수공법으로써 크랙실링이 일반화되어있고 과거 10여년에 걸쳐 이를 자동화하기 위한 연구노력이 활발히 진행 중이다. 본 논문은 미국을 중심으로 지금껏 개발되어진 크랙실링 자동화 로봇의 프로토타입을 간략히 소개하고 미 연방교통국(FHWA)과 텍사스 주 교통국(TxDOT)의 지원하에, 텍사스 오스틴 주립대학 건설자동화 연구소에서 개발된 크랙실링 자동화 로봇의 연구성과 및 1999년 현장실험 결과를 토대로 크랙실링 자동화 로봇의 타당성 및 적용성 그리고 개발기술의 응용성을 시험한다. 크랙실링 자동화 로봇의 개발과 활용을 통하여 도로의 수명 연장 및 년간 막대한 도로 유지보수 사업예산의 절감이 가능할 것으로 사료되며 개발된 자동화 기술은 추후 빌딩외벽, 대규모 저장탱크 등 도로 이외의 건축.토목 구조물에 발생된 균열의 탐지 및 보수에도 널리 활용될 수 있을 뿐만 아니라 동영상 처리기술 등의 멀티미디어 기술과 무선정보통신망을 응용한 본사와 현장간 실시간 안전진단 및 분석에도 그 활용효과가 클 것으로 기대된다.

키워드 : 건설자동화, 크랙실링, 유지보수, 로봇, 포장도로, 경제성, 생산성