THE DEVELOPMENT OF A MACHINE VISION ASSISTED, TELEOPERATED PAVEMENT CRACK SEALER

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ABSTRACT: Crack sealing is a maintenance technique commonly used to prevent water and debris penetration and reduce future degradation in pavement. The conventional crack sealing operations are, however, dangerous, costly and labor-intensive. Labor turnover and training are also increasing problems related to crack sealing crews. Automating crack sealing will improve productivity and quality, and offer safety benefits by getting workers off the road. The reduction in crew size and the increase in productivity of the automated sealing process will be translated directly into significant potential cost savings. The main objective of this study is to develop an automated system for sealing cracks in pavement, and to validate the developed system through field trials. A machine vision algorithm, which is composed of noise elimination, crack network mapping and modeling, and path planning, was developed to operate the proposed automated system effectively. Extension of the algorithms and tools presented in the study to other applications is also recommended for future studies.

KEYWORDS: Crack sealing, Pavement, Automation, Machine Vision, Path Planning

1. INTRODUCTION

Aging of our pavements is most visibly exhibited in the form of surface cracking. Surface cracking in pavements should be repaired because it increases pavement degradation, which can lead to the significant reduction of the service life of a pavement. If cracks in pavements are not sealed, surface water penetration can reduce the strength of the sub-base layers, which might result in broader cracks and potholes. Among various methods for repairing cracks in the pavement, crack sealing is an effective strategy utilized by maintenance authorities around the country. The conventional crack repair method is, however, dangerous, costly, and labor-intensive. Labor turnover and training are increasing problems related to crack sealing crews.

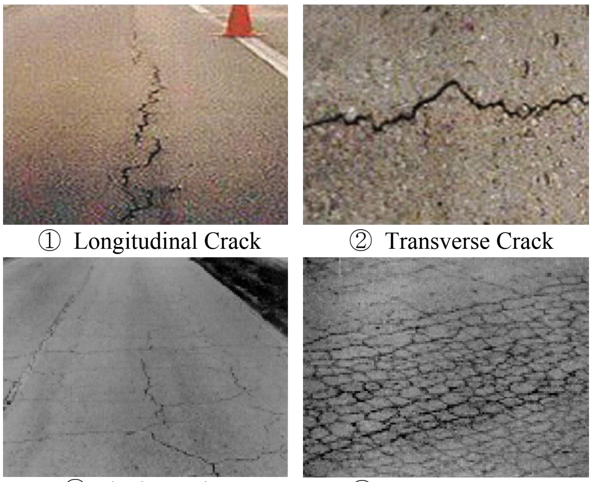
Automating pavement crack sealing process will improve productivity and quality, and will offer safety benefits by getting workers off the road. The reduction in crew size and the increase in productivity of the sealing process will also be translated directly into significant potential cost savings. Since 1990, several systems for automatically sealing surface cracks have been developed in highway construction and maintenance area. The primary objective of this study is to: 1) develop an Automated Pavement Crack Sealer(APCS), 2) briefly illustrate a machine vision algorithm developed for mapping and modeling the exact locations of pavement cracks to be sealed, including path planning, and 3) validate the technical feasibility of the APCS through several laboratory and field tests.

This study begins by describing the conventional crack sealing process in Korea as well as discussing some of the major research problems associated with the automation of pavement crack sealing. The system components of the developed APCS and machine vision algorithm are then illustrated. Performance(productivity) evaluation results of the APCS are discussed as well. Finally, conclusions are made concerning the value of automated pavement crack sealing and the applicability of the algorithms and tools presented in this study.

2. MAJOR RESEARCH PROBLEMS AND RELATED WORKS

2.1 Conventional Crack Sealing Process

In general, crack patterns existing on asphalt pavements are classified into the following four categories: 1)longitudinal, 2)transverse, 3)block, and 4)alligator cracks(Fig. 1). Among those, longitudinal, transverse, and block cracks are mainly repaired by sealing, while overlay or patching is used for repairing alligator cracks.



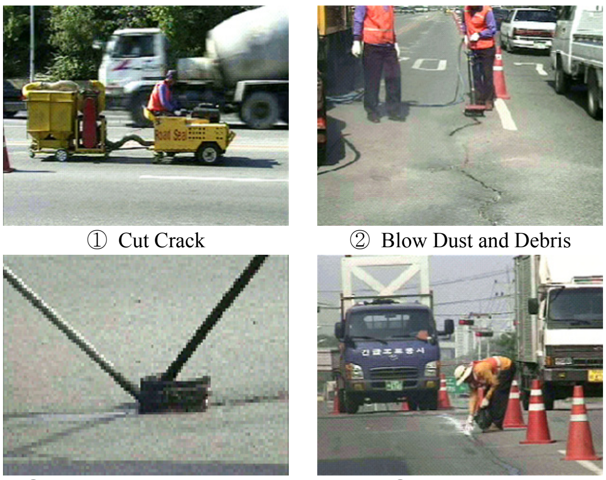
① Longitudinal Crack ② Transverse Crack

③ Block Crack ④ Alligator Crack

Fig. 1 Crack Patterns on Asphalt Pavements

Crack sealing is a preventive maintenance method, in which a sufficient amount of 170~180℃ sealant is placed along the spine of pavement cracks. In Korea, cutting cracks to be sealed in pavements is essentially required prior to sealing. As a result, sealed cracks can protect the sub-structure of the pavement from water and debris penetration; the crack sealing method thus can decrease crack broadening and prevent potholes. Such crack sealing procedures are as follows(Fig 2);

- Cut cracks to be sealed (width; 1.2~2cm, depth; 2~2.5cm) according to the construction specification regulation
- Blow dust and debris in cut crack network
- Seal by injecting 170~180℃ sealant into the cut cracks
- Finish the surface of sealed cracks by squeegeeing
- Cure the sealant



① Cut Crack ② Blow Dust and Debris

③ Inject and Squeegee Sealant ④ Cure Sealant

Fig. 2 Conventional Crack Sealing Process

2.2 Major Research Problems

For automatically sealing pavement cracks, the end-effector(turret) of the crack sealer must accurately and quickly trace the spine of each crack network and inject sealant into the crack network. It is due to the fact that productivity and quality of crack sealer are very important for its commercialization as well as the acceptance by the maintenance personnel. Major research problems related to the development of a crack sealer are as follows;

(1) Crack network mapping and modeling

Pavement images shown by digital CCD camera commonly include not only real crack networks, but also a wide variety of noises such as oil marks, skid marks, previously sealed cracks and inherent noises. Therefore, an algorithm that can extract only crack networks from the pavement images including the noises must be developed. Also, the algorithm must be able to accurately model the exact locations(x-y coordinates) of the extracted crack network so that the turret of the crack sealer can inject sealant into the spine of each crack network to be sealed. Crack network mapping and modeling is thus one of the most important research problems in developing any type of crack sealer.

(2) Path planning

There are many different types of pavement crack shapes, with occasionally complex morphologies. Possible paths can easily exceed 1,000,000 [7]. Objectives for crack sealing include minimizing distance and tool state switching. For automated crack sealing, the primary objective of path planning is to quickly find an optimal path, guaranteeing traverse of any kind of crack morphology in a given work space. In this study, an optimal path planning algorithm has been developed to generate the shortest traversal plan in a given crack network.

(3) Manipulator and End-effector Control

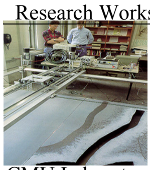
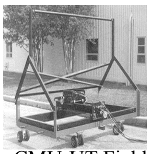
A crack sealer has to have 4 degrees of freedom to accurately move and seal along the spine of the crack networks. That is, X-axis and Y-axis movements are required to move in any directions on 2D surface. Z-axis movement (telescoping function) is also required to guarantee that cracks in a rutted pavement are sealed properly. In addition, the turret of crack sealer has to be rotated to effectively blow, seal, and squeegee along the spine of the crack network. Therefore, a motion control system is required to direct the crack sealer along the X-, Y-, and Z-axis and to rotate the turret of crack sealer.

In the development of an automated construction and maintenance system including the APCS, the ultimate goal would be to develop a commercial system which can be operated at manual crew speed or faster with desired accuracy. That is, the system will have to meet the productivity and quality of standard sealing crews in a conventional method. Compared to the conventional crack sealing operations, improving the operating speed in the APCS to be developed would be the most significant and critical factor for overall project success. Thus, effective and accurate crack detection, mapping and modeling, optimal path planning of the APCS and its manipulator and turret control will be the major tasks required to achieve the desired accuracy and operating speed.

2.3 Previous Research Works

During the last few years, several advanced countries have developed automated pavement crack sealing systems such as the CMU laboratory prototype(1990), CMU-UT field prototype(1992), CalDavis field prototype(1993), and UT field prototype(1995), ARMM(1999). Table 1 briefly describes the accomplishments and major concerns in each previous research work.

Table 1. Previous Research Works Related to the Automated Pavement Crack Sealing System

Previous Research Works	Accomplishments and Major Concerns
 CMU Laboratory Prototype(1990)	• Conceptual design of S/W and H/W for full automation • Crack detection, mapping and representation using digital image processing • Incomplete and unstable fabrication of H/W(X-Y manipulator) • Excessive processing time in the crack detection, mapping and modeling
 CMU-UT Field Prototype(1992)	• Development of a machine vision algorithm using sensor (vision and laser range scanner) fusion • Development of path planning algorithm using linked data structure • Fabrication of more robust H/W(XY-manipulator) and partial integration of S/W and H/W • Partial verification of fully automated crack sealing process • Excessive processing time due to still slow range scanning
 CalDavis Field Prototype(1993)	• Development of histogram based machine vision algorithm • Lack of accuracy in crack detection, mapping and representation • Limitations in types of crack to be sealed • Employment of multiple manipulator arms • Sealing speed of 16km/hour • Failure to attract private contractors or government department due to the expensive selling price(over US $55,000 to 850,000
 ARMM(1999)	• Suggestion of a man-machine balanced control process for effectively sealing pavement cracks • Development of a machine vision algorithm (manual mapping, line snapping and manual editing) using graphical programming and user-friendly control software • Development of greedy path planning algorithm using array data structure • Need to improve the design of turret and machine vision algorithm[8]

The hardware of the automated pavement crack sealing systems was incomplete in the early stage. The software for mapping and modeling crack network to be sealed and path planning were not efficient in terms of productivity, quality and accuracy for commercialization. In addition, the hardware and software developed were not integrated properly, causing inaccurate and inefficient movement in the automated pavement crack sealing systems. The resulting deeper understanding of such early attempts and the recent advances in the relevant robotic technologies have thus motivated these researchers to develop and examine more advanced pavement crack sealer, which can accurately and effectively represent and seal pavement cracks under any work environments.

3. MAJOR SYSTEM COMPONENTS AND OPERATION PROCESS OF APCS

3.1 System Components of APCS

The APCS developed through this study is composed of the following three units: 1) tow truck, in which a system operator controls the APCS using a PC, 2) a sealant melter that supplies a 170~180℃ sealant to the APCS, and 3)crack sealing unit for blowing, sealing and squeegeeing cracks in pavements(Fig. 3).

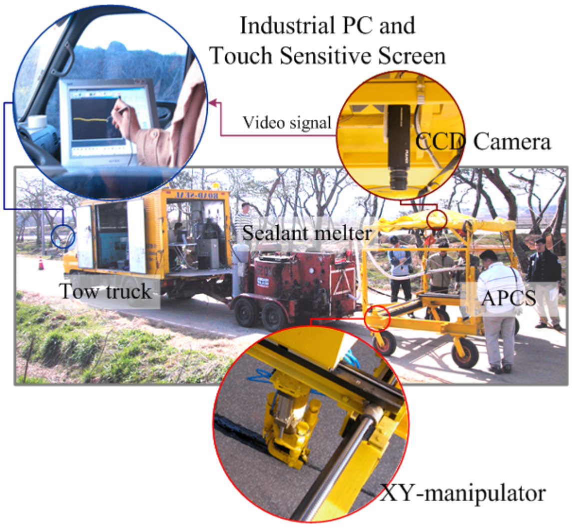


Fig. 3 Automated Pavement Crack Sealer(APCS)

The major components of the crack sealing unit of the APCS are as follows; 1) XY-manipulator with cart, gantry, turret, and CCD camera, 2) control box, 3) industrial PC with frame grabber and touch sensitive screen, and 4) power supplies. A machine vision software is also an essential component required to operate the APCS. This software is mainly composed of noise elimination, crack network mapping and modeling, and optimal path planning algorithms. In designing and fabricating the APCS, the following factors were especially considered.

- Designing the table(frame) of the XY-manipulator that is not twisted against the pavement level and various work situations
- Designing the machine vision algorithm that is not

affected by shade and pavement surface reflection

- Mounting the lighting system for working at night to minimize road-user-costs and increase productivity
- Rotating the turret of the APCS to effectively blow, seal, and squeegee the crack network to be sealed
- Designing turret structure for effectively sealing cracks in pavement with rutting(need to add telescoping function to the turret)
- Designing turret structure to effectively squeegee the sealant injected on the pavement cracks(turret with squeegeeing device of ‘V’ or ‘U’ shape)

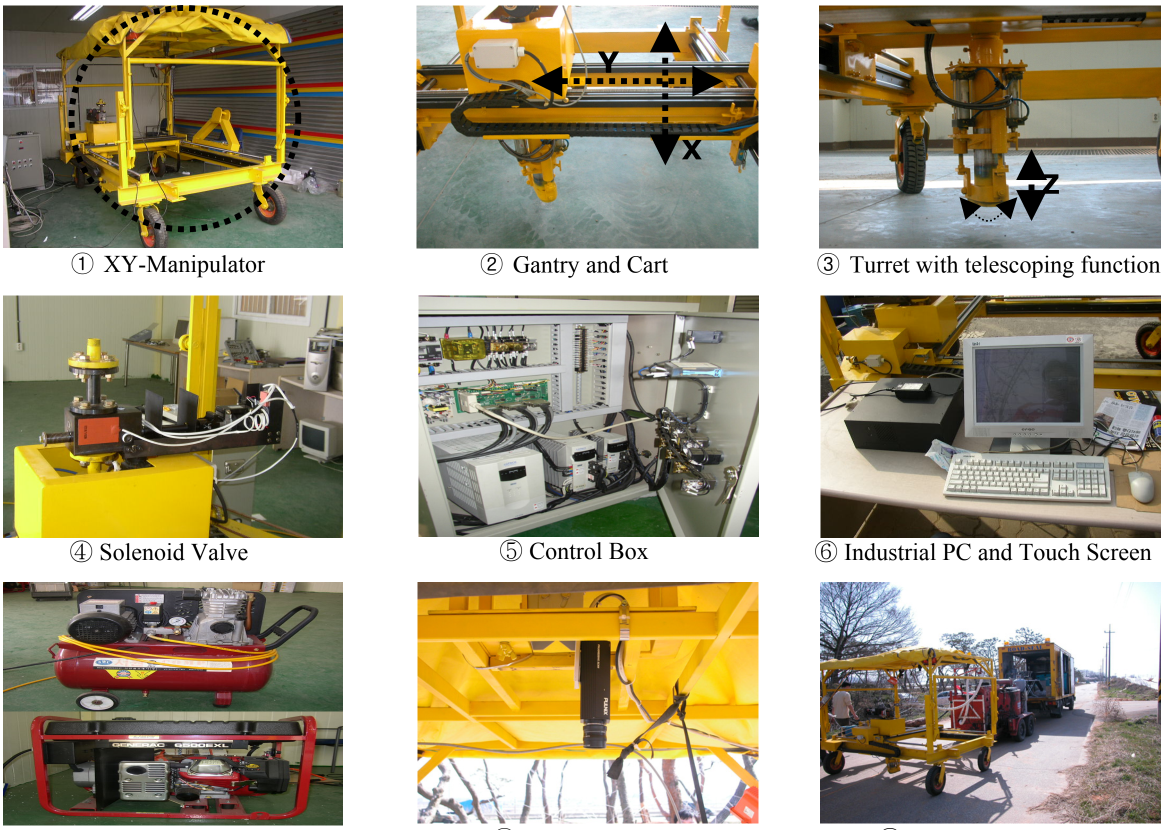
Based on the results of the major considerations, a field prototype of the APCS was designed and fabricated as shown in Fig. 4. A more detailed description of the system components and their functions of the APCS is illustrated elsewhere[9].

3.2 Crack Sealing Process of the APCS

The APCS uses an XY-manipulator with a rotating turret to blow, seal, and squeegee pavement cracks in one pass, thus greatly improving its productivity. While the manipulator is moving within its work space, 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 APCS through a work cycle, the following six steps are required;

- Acquire pavement image including the crack network through digital CCD camera installed on the superstructure of the APCS and frame grabber board installed in the PC
- Stop the APCS if crack network exist on the operator's touch sensitive monitor
- Automatically eliminate noises for mapping and modeling the crack network(This process is required only for the case of fully automated crack network mapping and modeling to be explained in Section 4.1)
- Extract the exact spine of the crack network using the developed crack network mapping and modeling algorithm (In the APCS, the system operator can map and model the crack network to be sealed in a given work space by both automated and semi-automated methods selectively.)
- Automatically perform the optimal path planning, based on the results of mapping and modeling for the crack network
- The APCS performs air blowing work, injects sealant into the crack network and squeegees the sealant according to the results of the path planning

Fig. 5 describes the man-machine balanced, teleoperated pavement crack sealing process in an extremely simplified form.



① XY-Manipulator ② Gantry and Cart ③ Turret with telescoping function
④ Solenoid Valve ⑤ Control Box ⑥ Industrial PC and Touch Screen
⑦ Air Compressor and Generator ⑧ CCD Camera ⑨ APCS in Field trial

Fig. 4 Field Prototype of the APCS

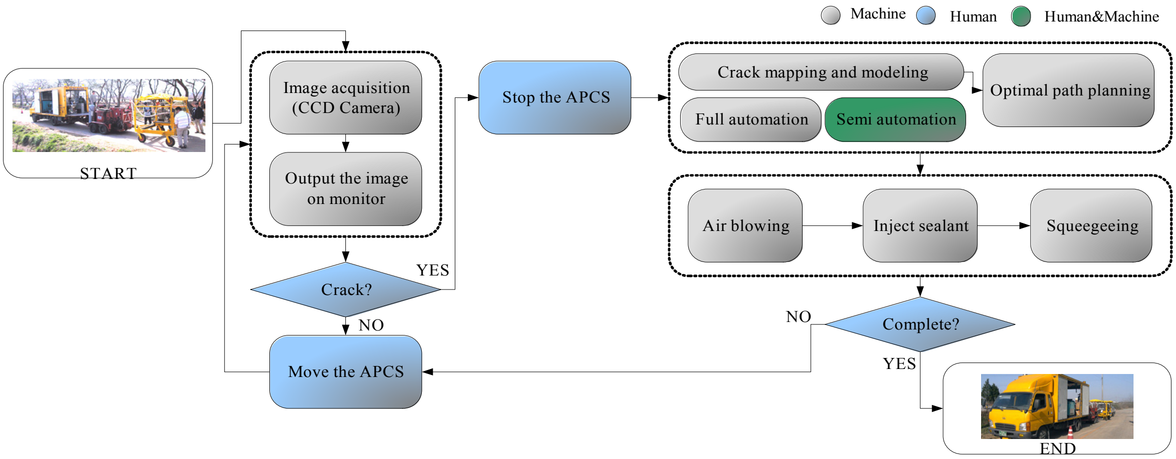


Fig. 5 Operation Process of the APCS

4. A MACHINE VISION ALGORITHM FOR AUTOMATED CRACK SEALING

In general, crack network mapping and modeling algorithm can be sensitively affected by conditions such as shade, intensity of pavement surface, and brightness. Therefore, in the APCS, the crack network detection, mapping, and modeling is operated in two ways: ‘full automation’ and ‘semi-automation’. A unique machine vision algorithm has been developed for the automation of pavement crack sealing.

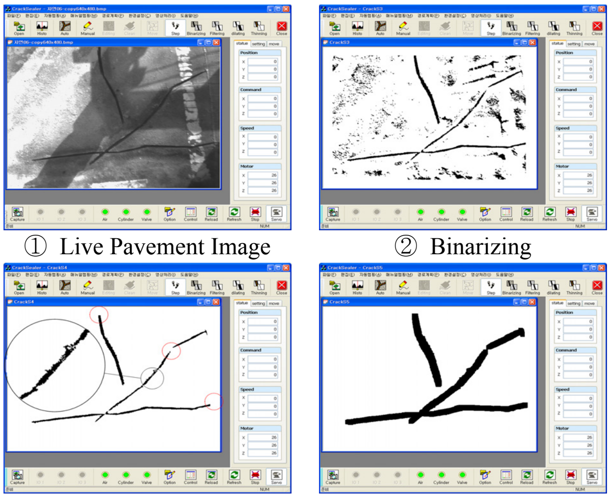
4.1 Fully Automated Crack Network Detection, Mapping, and Modeling

Fully automated crack network detection, mapping, and modeling process mainly includes ‘binarizing and noise elimination’ and ‘crack network mapping and modeling’.

(1) Binarizing and Noise Elimination Algorithm

A binarizing and noise elimination algorithm must be developed so that the turret(end-effector) can accurately trace the exact spine of the crack network and inject sealant into them. Binarizing aims to effectively distinguish crack network from the noisy pavement image. The binarizing algorithm, which is designed to automatically set up a threshold value, represents the intensity of pavement image(Fig. 6-①) as black(0) and white(255)(Fig. 6-②). Crack network is randomly extracted after the binarizing process. Therefore, this study developed a noise elimination algorithm for the perfect extraction of crack network in a given work sapce. The noise elimination algorithm is performed as follows.

- Grouping connected pixels with the binarized result image
- Extracting the features of each group
- Automatically evaluating the group according to the average intensity, dimensions, circumference, circumference-dimension rate, diameter, thickness, and roundness ($4\times\pi\times A/L^2$) to eliminate noises completely (Fig. 6-③).



① Live Pavement Image ② Binarizing

③ Noise Elimination ④ Dilation

Fig. 6 Binarizing, Noise Elimination and Dilation Process

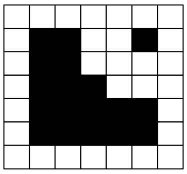
As shown in Fig. 6-③, the result of the noise elimination process algorithm shows a rough boundary of the crack network and unconnected pixels in the inner part of each crack line. Thus, this study applied the dilation process to the image in which noise was eliminated(Fig. 6-④).

(2) Crack Network Mapping and Modeling Algorithm

In this study, an edge thinning algorithm was used for automatically mapping and modeling crack network extracted after binarizing, noise elimination, and dilation process. The objective of the edge thinning algorithm is to erase the outline(edge) of each crack line in the network until one pixel remains. As a result, remained pixels are located in the spine(center) of the crack network, and connected to each other in the same group. However, most of the previous edge thinning algorithms such as those of Suen[1], Wang[2], Guo[3], Hall[4] and Zhang[5] developed to effectively recognize alphabet letters could not be applied to the crack network mapping and modeling in terms of time and accuracy. This study thus utilized a parallel edge thinning algorithm using a weighted number[6]. The parallel edge thinning algorithm is based on the 3×3 mask composed by 9 pixels, and a pixel 'P' has 8 pixels(X1~X8) nearby(Fig. 7-①). A weighted number is the number of black pixels existing the pixel 'P' nearby(Fig. 7-②).

x1	x2	x3
x8	p	x4
x7	x6	x5

①8-Neighbored Pixels



② Input Image

0	0	0	0	0	0	0
0	3	3	0	0	9	0
0	5	6	0	0	0	0
0	5	7	6	0	0	0
0	5	8	7	6	3	0
0	3	5	5	5	3	0
0	0	0	0	0	0	0

③ Weighed Number

Fig. 7 3x3 Mask and Weighted Number

A black pixel 'P' must be erased in the case of the same condition of Fig. 8 after the weighted number is determined.

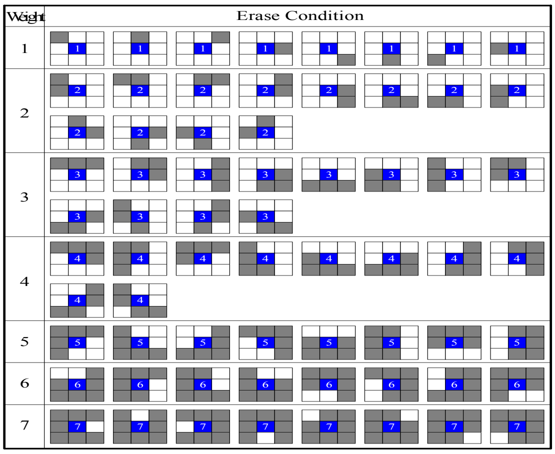
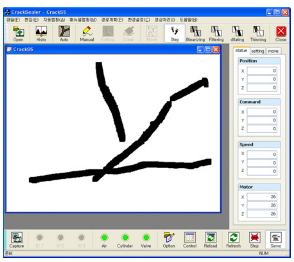
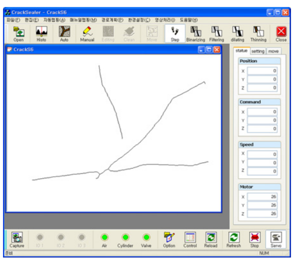


Fig. 8 Erase Condition of a Pixel According to Weighted Number

Fig. 9 is the result of applying the parallel edge thinning algorithm using a weighted number to a crack image. The thinned crack network(Fig. 9-②) is composed of several lines that are located in the spine of the crack network. The pixels of each thinned crack line are then saved in the memory so that the turret of the manipulator can move along the thinned crack line.



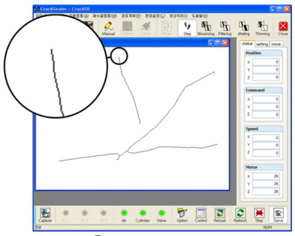
① Dilated Crack Image



② Parallel Thinning Algorithm

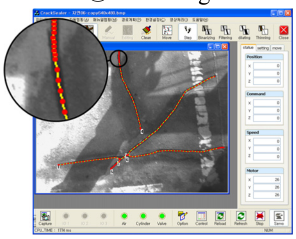
Fig. 9 Parallel Edge Thinning Algorithm Using Weighted Number

The result of the crack network mapping and modeling is represented for the operator to confirm errors(Fig. 10-②). Edge linking is then performed to connect pixels(Fig. 6-③) that might be erased wrongly in the process of binarizing or noise elimination(Fig. 10-③). Finally, the result of the automated crack network mapping and modeling is output as a text type and sent to a control program(Fig. 10-④).

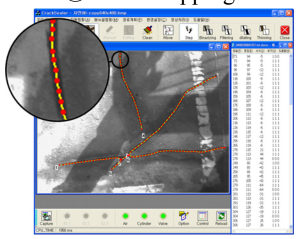


① Thinning

② Path Mapping



③ Edge linking



④ Complete Modeling

Fig. 10 Automated Crack Mapping and Modeling

4.2 Semi Automated Crack Network Detection, Mapping and Modeling

Semi automated crack network mapping and modeling process is as follows(Fig. 11);

- Draw lines along the crack network
- Create node points on the drawn lines at regular intervals
- Create 5 x 41 pixel sized local boxes centered on the node points
- Perform local binarizing(0;background, 1;crack) in the created local boxes
- Move node points on the drawn lines into the center of gravity of the largest set composed '1'
- Show the result of crack network mapping and modeling on the touch screen in order to confirm errors
- Perform manual editing, if any errors exist in the result of crack network mapping and modeling

The test results showed that the semi automated crack network mapping and modeling algorithm was superior in terms of accuracy over the fully automated crack network mapping and modeling algorithm, but inferior in terms of productivity. Using neural network, the fully automated crack network mapping and modeling algorithm illustrated is currently being upgraded in order to guarantee superior performance in terms of both accuracy and productivity.

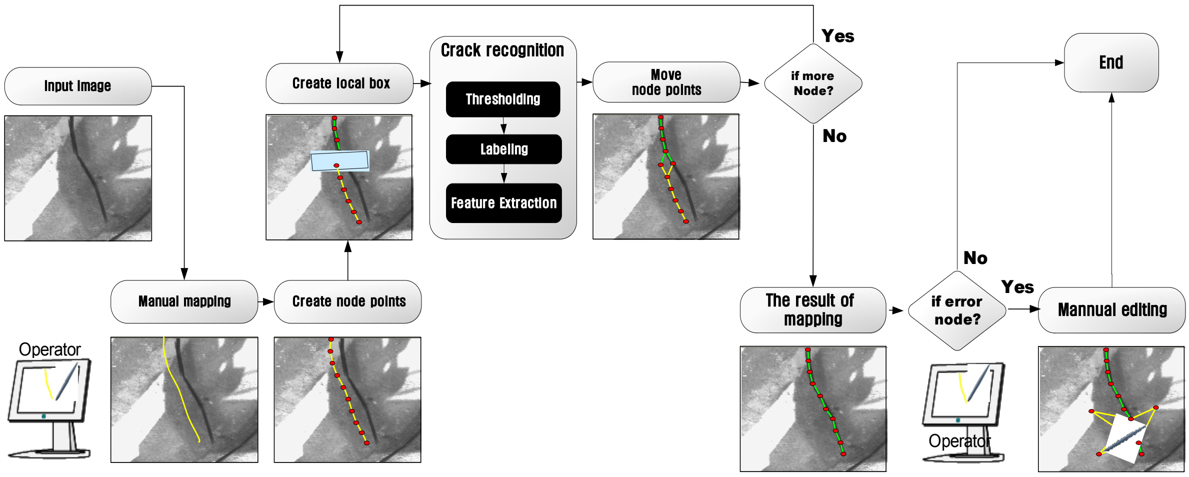
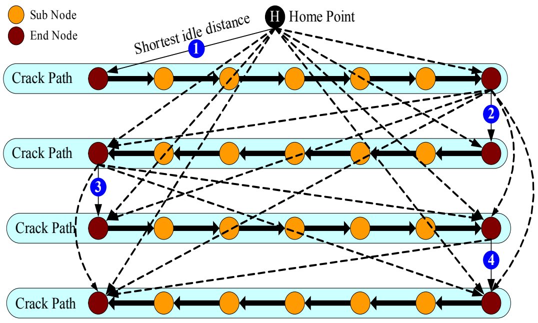


Fig. 11 Semi-Automated Crack Network Mapping and Modeling

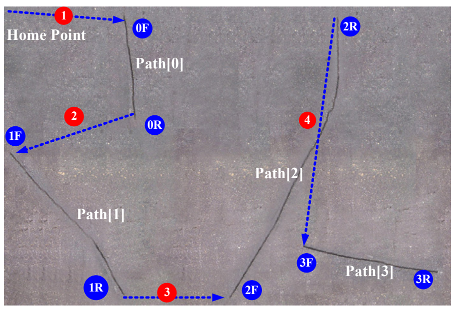
4.3 Optimal Path Planning

If there are several lines in the crack network extracted from a pavement image, the number of path is 2^n x n!. Greedy path planning algorithm was designed for crack sealing in the past[7]. The nearest node point from home point among the end node points of each crack network is the start node point for sealing, and the turret injects sealant along the crack network until the turret reaches the other end node point in the greedy path planning algorithm(Fig. 12-①, ②). However, the path planned by the greedy algorithm is not often the optimal path. This study thus developed an optimal path planning algorithm which can always provide the shortest path. In the optimal path planning algorithm, a computer calculates the lengths of all paths so that the shortest path can be selected(Fig. 12-③, ④). The results of test showed that the optimal path planning algorithm is effective if the number of crack lines in a network is 6 or less, and the greedy path planning algorithm is useful if the number of crack lines in a network is more than 7.

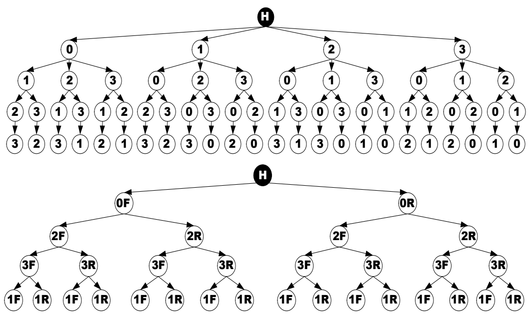
The control program developed is designed to automatically select a path planning algorithm according to the number of crack lines in a given network.



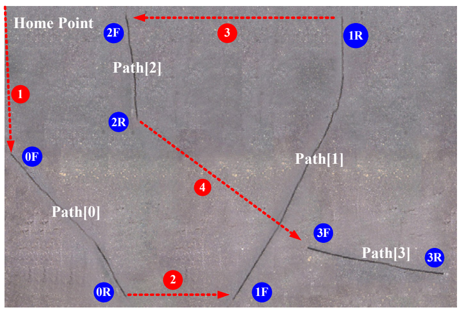
① Greedy Path Planning Algorithm



② The Result of Greedy Path Planning
(Idle Path Distance= 945Pixels)



③ Optimal Path Planning Algorithm



④ The Result of Optimal Path Planning
(Idle Path Distance= 882Pixels)

Fig. 12 Path Planning Algorithm

4.4 Integration of Hardware and Software

The APCS is mainly composed of an image capture module, machine vision module, and hardware control module. The integrated system of hardware and software is required to allow the APCS to accurately blow, seal, and squeegee along the spines(x, y coordinates) of each crack lines in a crack network extracted through the mapping, modeling, and path planning process. The image capture module and hardware control module are developed as a type of a dynamic link library(DLL), and imported into the machine vision module. The system operator can easily control the APCS with user-friendly graphical interface(Fig. 13).

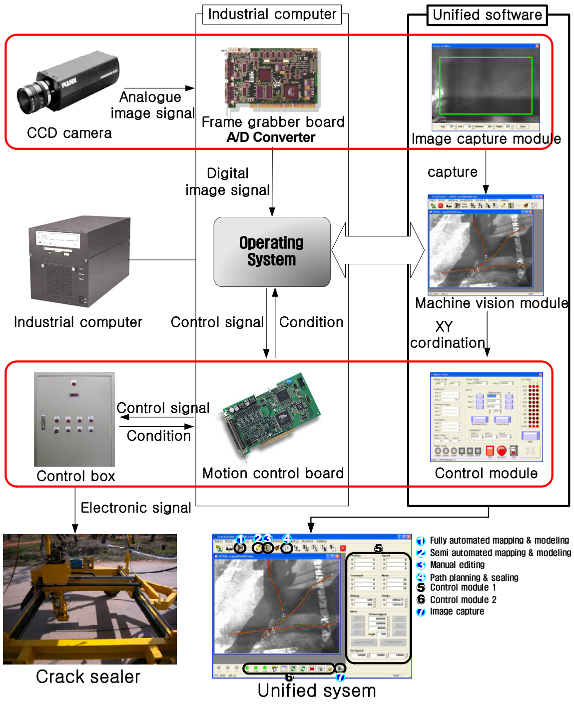


Fig. 13 Integrated System Architecture of APCS

5. FIELD TEST RESULTS

5.1 Field Demonstrations of the APCS

This study performed several laboratory tests and 3 field demonstrations to complete the prototype of the APCS. Especially, the field demonstrations were performed to evaluate the overall performance (productivity, quality and safety) of the developed APCS(Fig. 14). The field demonstration procedure is as follows;

- Connect the tow truck, sealant melter, and XY-manipulator
- Set up the computer and touch sensitive screen in the tow truck cabin, and connect them to the control box.
- Connect the control box to a XY-manipulator with a control cable
- Move the APCS to the work space
- Calibration of a work space
- Acquire image, and map and model crack network to be sealed
- Blow, seal, and squeegee the crack network

① Setting the APCS ② Cutting Crack ③ Modeling Crack Network ④ Crack Sealing 1 ⑤ Crack Sealing 2 ⑥ The Result of Crack Sealing

Fig. 14 Field Demonstration Procedure of the APCS

The results of the field tests showed the followings: 1) the major components(cart, gantry, turret consisting of the XY-manipulator) of the APCS were moved adequately according to the on/off trigger signals from the machine vision and control software; 2) The turret was moved accurately along the spines of each crack network, and injected the sealant into them; 3) 'U' typed squeegee pressed sealant effectively; 4) The normal speed of the turret was measured to be about 18~20cm/sec; 5) The accuracy of the machine vision algorithm including noise elimination, crack network mapping and modeling, and path planning was measured to be over 86%; and 6) Quality of work done was on the whole excellent. On the other hand, the errors in the machine vision algorithm were correctly adjusted by manual editing with rubber banding capability so that the accuracy of the vision might be 100%.

5.2 Productivity of the APCS

This study measured the productivity of the developed APCS to compare with that of a conventional crack sealing method that generally shows the productivity of 1.2km/day with about 2 trucks, 1 sealant melter, and 12 labors. The test conditions for automation and conventional method were set up as similar as possible. Table 2 shows the number of resources required to seal pavement cracks with the automation method, and Fig. 15 shows the real test bed that was made to measure the productivity of the APCS.

Crack networks in the test bed were composed of two transverse cracks of a total length of 4 m and three longitudinal cracks of 34.9m. The result of image processing time measurement shows that the time required for image capture, digital image processing, and path planning are 0.1sec, 0.5sec, 0.3sec, respectively.

Table 2. Resources for Automated Crack Sealing

Labor		Equipment	
Operator	1	tow truck	1
Labor for cutting	1	sealant melter	1
Cleaning and Blowing	1	XY-manipulator	1
Labor for controlling sealant melter	1	-	
Talc	1	-	
Foreman	1	-	
Total	6		3

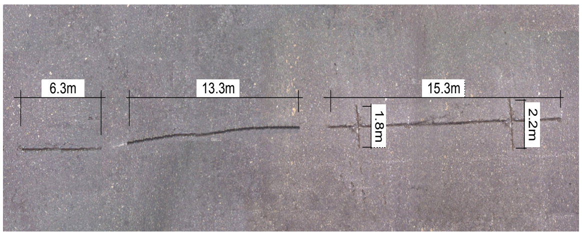


Fig. 15 A Test Bed to Mesure Productivity

The real work space of the APCS is 1.55m × 0.9m, and the speed of the turret is about 20cm/sec as ‘not sealing’, 18cm/sec as ‘sealing’. This study measured the productivity of the developed APCS based on the productivity data and evaluation model(Fig. 16).

In the productivity evaluation model, the sum of length of crack networks(L) divided by the moving time(T) and the image processing time(I) and the crack sealing time(S) gives the productivity(P) of the APCS. The prototype of the APCS should stop 44 times for sealing the entire crack networks in the test bed illustrated in Fig. 15. Work time required in each work space was measured with stop-watch method. As a result, the productivity of the APCS is 3.3m/min based on the measured productivity data and evaluation model(Fig. 16).

- The productivity of the APCS(P)

$$P = L / (T+I+S) = L / [(Tb+(Ta \text{ or } Tc)) + (Ia+Ib+Ic) + S]$$
$$= 38.9m / [(173+262) + 40 + 216)] = 38.9m / 691sec$$
$$= 0.057m/sec \rightarrow 3.3m/min$$

Therefore, the daily productivity of the APCS would be 1.59km/day(=3.3m/min × 480min/day). When compared with the productivity of a conventional crack sealing method(1.21km/day), that of the APCS was higher by as much as 0.39km/day. The productivity of the APCS would be much higher, when considering the night time operations and possible improvements (size of the XY-manipulator) of the developed APCS.

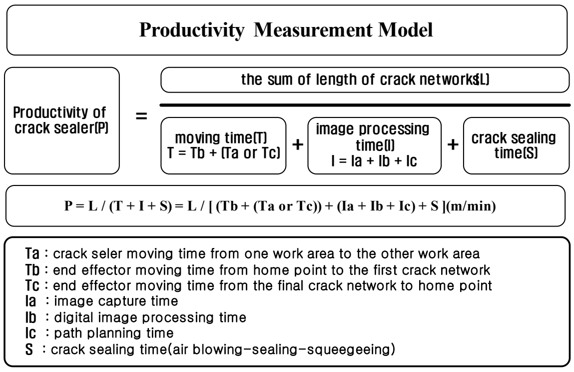


Fig. 16 Productivity Measurement Model

6. CONCLUSIONS

In conclusion, the advantage of the automating conventional pavement crack sealing process is clear. Recent field trials of the full-scale APCS appear to support this conclusion as well.

In this study, a machine vision algorithm for noise elimination, crack network mapping and modeling, and path planning was developed. The test results of the developed machine vision algorithm showed that its accuracy was over 86%, and the processing time was about 0.9sec/image. The prototype of the APCS was developed by analyzing and investigating previously developed pavement crack sealing systems and enabling state-of-the-art technologies. Laboratory and field demonstrations of the developed APCS were conducted for evaluating and verifying its overall performance and technical feasibility. Major components of the APCS were operated without any problems and the blowing, sealing and squeegeeing speed of the turret was measured to be about 18~20cm/sec.

Six labors were required to seal cracks with the APCS, while the conventional crack sealing method required 11~12 labors. Daily productivity rate of the APCS was analyzed and found to be 1.59km/day. The reduction in crew size and the increase in productivity of the automated sealing process will be also translated directly into significant potential cost savings.

Finally, it is anticipated that the man-machine balanced, teleoperated crack sealing process presented in this study would be applicable to a wide variety of infrastructure cracks and joint sealing. Partial modifications of the algorithms and tools presented in this study would eventually have broader applications in automation of infrastructure inventory geometric data acquisition and use or inspection and maintenance of civil works.

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