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Review

Chronological development history of *X–Y* table based pavement crack sealers and research findings for practical use in the field

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ABSTRACT

During the last two decades, several teleoperated and machine-vision assisted systems have been developed to automate the overall process of routing and sealing pavement cracks. Productivity improvement, improved safety and quality, and reduced road user costs have motivated these developments. This paper presents the chronological development history of *x–y* table based pavement crack sealers, which have been developed and demonstrated since the early 1990s, and compares their technical advances. This paper also discusses primary research findings in machine vision software and hardware designs of an automated pavement crack sealer to be newly developed for practical use in the field. Finally, conclusions and recommendations are made concerning the value of implementing and practically using the automated pavement crack sealer.

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1. Introduction

Crack sealing, a routine and necessary part of pavement maintenance, is a dangerous, costly, and labor-intensive operation. During the last two decades, several systems based on *x–y* table for automatically

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routing and sealing pavement cracks have been developed. Examples include: 1) CMU laboratory prototype (1990) [1,2], 2) CMU-UT field prototype (1992) [2,3], 3) UT Automated Road Maintenance Machine (ARMM) (1997) [3–6], and 4) Automated Pavement Crack Sealer (APCS) (2004) [7,8]. Since automating pavement crack sealing can improve safety, productivity, and quality, and also reduce road user costs, there has been extremely large demand for practical use of automated pavement crack sealers in the areas of road construction and maintenance. While early works sought to completely automate crack mapping and sealing activities, experience and the resulting deeper understanding of the enabling technologies have highlighted the importance of finding a desirable balance between human and machine functions in the control of automated pavement crack sealers.

Through trial and error and about 20 years of perseverance, the APCS, the most recent deliverable research, has achieved a desirable balance between manual and automated functions for automated pavement crack sealing. Recent field trials of the full scale APCS have also indicated that automated pavement crack sealing is now technically, economically, and financially feasible. Despite such numerous efforts to automate conventional crack sealing operations, lessons learned from previous system developments and field trials have indicated that several improvements in both software and hardware designs are still required for their practical application in the field. The primary objective of this paper is to present overall software and hardware design requirements for practical use of an automated pavement crack sealer in an effort to fulfill the aforementioned demand in road construction and maintenance. This paper presents the chronological development history of *x*–*y* table based pavement crack sealers, which have been developed and demonstrated since the early 1990s, and compares their technological advances. This paper then proposes primary research findings in machine vision software and hardware designs of an automated pavement crack sealer to be newly developed for practical use in the field. A conceptual hardware design for a new model is proposed in this paper as well. Finally, conclusions and recommendations are made concerning the value of implementing and practically using the automated pavement crack sealer.

2. Automation needs

Crack sealing is a maintenance technique commonly used to prevent water and debris penetration and reduce future pavement degradation. The conventional crack sealing operations are, however, dangerous, costly, and labor-intensive. With respect to crack sealing crews, labor turnover and training are also increasing problems. Automation of the crack sealing process would improve productivity and quality, and offers safety benefits by getting workers off the road. The reduction in crew size and the increase in productivity of the automated sealing process are expected to be translated directly into significant cost savings.

For example, APCS field test results indicated that the daily productivity would be 1.59 km/day. Compared with the productivity of a conventional crack sealing method (1.21 km/day), that of the APCS was as much as 0.39 km/day higher. On-site tests and a performance analysis of the APCS demonstrated that its use would allow a 50% reduction of the labor force and 32.5% enhanced productivity [8]. Furthermore, when considering nighttime operations and possible hardware improvements of the developed APCS, the productivity of the APCS would be even higher.

The results of an economic feasibility analysis of the APCS also revealed that automating the conventional crack sealing operation is highly feasible and would potentially bring enormous cost savings. Information for the analysis was gathered to estimate costs and benefits, analysis perspectives were chosen, and the market was studied. Rate of return, benefit–cost ratio, break-even point, and sensitivity analyses were used to verify the economic feasibility of implementing the automated method in place of the conventional method. Under assumptions such as an APCS purchase cost of US $72,000, 100 working days per year, use of 1 APCS, 10% MARR, a 10 year planning horizon, a 50% reduction in labor force, etc., it was anticipated that a contractor would be able to cut conventional maintenance costs by 43.6%. With the above assumptions, the economic analysis results of the APCS also showed a value of 122.5%, 5.5, a 15 month in rate of return period, benefit–cost ratio, break-even point, respectively, thus making the use of APCS highly attractive. The results of a sensitivity analysis and predictions pertaining to reduction of road user costs obtained using Paramics™ simulation software have been presented elsewhere [8].

3. Automated pavement crack sealing systems

In this chapter, *x*–*y* table based systems developed since the early 1990s for automatically routing and sealing pavement cracks are briefly described. Technological details of the systems are presented, and related research accomplishments, concerns, and technical advances are identified. Visual appearances of each prototype system are illustrated as well.

3.1. Chronological development history

Table 1 briefly describes the accomplishments and major limitations of previous research works. The hardware of early *x*–*y* table based pavement crack sealing systems was incomplete in the early stage. At the same time, the software for mapping and modeling the crack network to be sealed and path planning were not efficient in terms of productivity, quality, and accuracy for practical use in the field. In addition, the hardware and software were not integrated properly, causing inaccurate and inefficient movement of the automated pavement crack sealing systems. The experience acquired from such early attempts and recent advances in relevant robotic technologies motivated authors to develop more advanced pavement crack sealer (APCS). Although the APCS employs a unique man-machine interfaced control process and provides innovative technical advances compared to previous research works [1–6,10], they have not been practically used on sites due to limitations in their hardware and software. Detailed comparisons and several limitations regarding the control paradigm, machine vision software, and hardware in the *x*–*y* table based pavement crack sealers developed in previous research works are presented in Sections 3.2–3.4.

3.2. Evolution of the control paradigm

Complete autonomy [1,3] could be achieved for the whole process (image acquisition, crack detection and mapping, path planning, blowing, sealing, and squeegeeing) of automated pavement crack sealing, but usually at a cost, speed, and accuracy that is impractical and unacceptable. Complex evolution of the control paradigm has resulted in a functional production prototype system [4–6,9,10] that achieves a good balance between manual functions and automated functions by taking advantage of the respective strengths of man and machine in the whole process. Teleoperation based on remote video, man-machine interfaces, machine vision, and graphical programming alone can achieve benefits of automation in the unstructured pavement crack sealing work environment. Lessons learned from system developments and field trials have also indicated that computer assistance in the form of man-machine interfaced graphical programming and machine vision is essential and can cost-effectively help to achieve improvements in the productivity and quality of automated methods. Considering recent successful developments in teleoperated construction field robots, it is thought that evolution toward teleoperation as a control paradigm of the automated pavement crack sealer is highly desirable. The ARMM and the APCS