

Real-time Image Scanning System for Detecting Tunnel Cracks Using Linescan Cameras

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ABSTRACT

In this paper, real-time image scanning system using linescan cameras is designed. The system is specially designed to diagnose and analyse the conditions of tunnels such as crack widths through the captured images. The system consists of two major parts, the image acquisition system and the image merging system. To save scanned image data into storage media in real-time, the image acquisition system has been designed with two different control and management modules. The control modules are in charge of controlling the hardware device and the management modules handle system resources so that the scanned images are safely saved to the magnetic storage devices. The system can be mounted to various kinds of vehicles. After taking images, the image merging system generates extended images by combining saved images. Several tests are conducted in laboratory as well as in the field. In the laboratory simulation, both systems are tested several times and upgraded. In the field-testing, the image acquisition system is mounted to a specially designed vehicle and images of the interior surface of the tunnel are captured. The system is successfully tested in a real tunnel with a vehicle at the speed of 20 km/h. The captured images of the tunnel condition including cracks are vivid enough for an expert to diagnose the state of the tunnel using images instead of seeing through his/her eyes.

Keywords: Linescan Camera, File Caching, Machine Vision

1. INTRODUCTION

As display and graphics technology develop, researchers have devised new equipments. Linescan camera is one of the newly devised equipments for the purpose of taking real-time pictures. Our designed system adapts the linescan camera to take shots of tunnel images. Until now, many tunnel experts went into tunnels to inspect their condition, keeping track of width of cracks and their growth. If the crack size and width are beyond the prescribed safety standards or the crack growth rate is faster than usual contingency plan is activated. As far as diagnosis is concerned, experts have done their work well. However, they often experience serious injuries on their necks and eyes since they spend lots of time inspecting the cracks usually in dark and hazardous conditions.

In this paper, a highly efficient system is de-

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signed to take tunnel images in real time. With this system, people only need to drive the system-mounted vehicle to capture tunnel images; thereafter they diagnose the status of tunnels at a convenient place, not in the field. Also crack growth is measured and then data is accumulated and analysed periodically. This method must be a more reliable and safer way to diagnose tunnel conditions than the conventional method of depending on human perception alone in a dark and hazardous tunnel.

The system consists of two sub-systems: image acquisition system and image merging system. The image acquisition system captures tunnel images and the image merging system combines the consecutive sub images into one extended image of the tunnel wall. The image acquisition system consists of control and management modules. The control module is in charge of controlling the hardware devices and the management module allocates the system resources so as to get images without system lag. The image acquisition system uses magnetic hard disk instead of the tape as a storage device for saving images. Though the tape accommodates large storage capacity, it is not fast enough to save images in real-time mode. But magnetic disk provides enough storage space and provides high-speed file transfer rate. Therefore, the system uses the magnetic storage disk instead of the tape. The system has been tested on two different experimental environments: in the laboratory and in the field.

In the following section, we review previous related researches followed by a brief explanation of the implemented system. Experimental environment is described and results are shown in the next section. Finally, our conclusion and future works will be discussed.

2. PREVIOUS WORK

Linescan camera is used in a lot of fields, especially in vision-based applications[1-4]. Also

it is broadly used to find errors through checking products in real-time in manufacturing companies. Several researchers generated 3D models by using a special-purpose vehicle with linescan cameras. While driving the vehicle, 3D buildings are generated and images are taken and used for making texture maps[5].

A few companies make tunnel image acquiring systems. Most of them use infrared cameras to acquire images. Though the system has already been used for diagnosing the crack width in European countries, infrared cameras cannot give high-resolution images. Because of highly strict standards, some countries cannot use the foreign image acquisition system using infrared cameras to diagnose tunnel conditions. Also some tape based tunnel image acquisition systems have been designed, but these systems do not guarantee real-time image capturing[6-8].

In Japan, a specific vehicle was designed for tunnel-scanning which can move on road as well as on track and uses four cameras and fifteen halogen lamps. However, using many lamps caused calorific problem. Also, because the speed of the vehicle was relatively slow, its efficiency was impaired[1,2,7].

In France, threading infrared ray scanner was installed for the experiment and while scanning a tunnel its temperature, water leakage and the air inflow was detected. Telemeter and odometer were also used to record correct position of objects such as the crack and the position of vehicles. However, the inaccuracy of its image as well as the slow speed of the vehicle at 5 km/h showed the scanner's inefficiency[8].

3. SYSTEM ARCHITECTURE

3.1 Image file format

Most digitized images are saved into encoded or compressed file formats to reduce disk storage usage. There are two different compression tech-

niques: lossless and lossy compression. In the late 1970s, research about lossless image compression techniques began and these techniques were based on statistical and dictionary methods of compression. However, these compression techniques did not tend to perform well on photographic images. Researcher tried to find more effective methods. Therefore, by the late 1980s extensive researches were done by taking advantage of known limitations of the human eye and these efforts resulted in finding lossy compression. The compression shows the high performance even if it utilizes lossy compression.

Currently lossless and lossy compression methods are well designed so as to reduce disk space usage[9,10]. Even if compressed images are efficient in reducing storage usage, it cannot be used in some applications. For example, for the case of diagnosing or analysing medical and crack or tunnel images, the images must not be lossy. The lossy information may cause serious problems in diagnosing the status. It may result in wrong judgment on the safety status.

The system is designed by adopting one of the lossless image compression methods. The designed system has been tested in several experimental settings. It is found that even though the compression algorithm can reduce space usage, it can affect other system modules in which a fairly expensive computation is required because of lossy compression. Hence, the system is designed not to apply the compression methods. The system adopts RAW image file format which is similar to well known BMP. In contrast to BMP file format, the RAW image file format does not have the header. In our system, the header information is not necessary because the system already knows image width, height and colour information.

3.2 Linescan camera configuration

Linescan camera consists of optical and electric parts. Fig. 1 shows the camera block diagram and a linescan camera used.

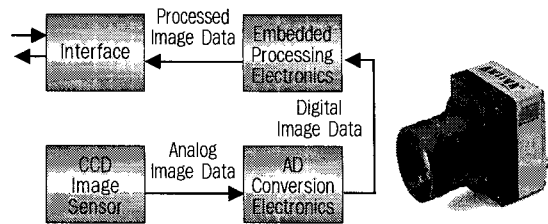


Fig. 1. Camera Architecture Block Diagram (left) and AViVA M2 CL (right).

Whenever the optical camera using CCD image sensor takes images, it sends the captured analogue data to the electric parts of system to convert into digitized format. After being converted into digitized data, the image data are directly sent to PC-based image grabber board. And then the data are extracted from the grabber board by using software systems. Both the grabber board and the linescan camera have their own attributes, which can be directly changed using serial communications. Changing attributes of the grabber board and the linescan camera is necessary while the system is taking pictures. The capturing speed of the linescan camera is associated with the vehicle speed on which linescan camera system is mounted. If the capturing speed of the linescan camera is not properly adjusted to the vehicle speed, the tunnel image will be improperly distorted: stretched or contract compressed. The used linescan camera and the grabber board's specifications are shown below:

Linescan Camera : AViVA M2, ATMEL Corporation.

Data rates : 60Mpixels/s

Grabber board : X64-CL, CORECO IMAGING Corporation.

Data rates : 255MB/s per input channel

The grabber board is mounted on the PCI slot of the PC. And the linescan camera is linked to the input channel in the grabber board. To cover wider surface area of the tunnel walls, the linescan camera uses wide-angle lens.

3.3 Image acquisition system

The overall system consists of two different subsystems: the image acquisition system and the image merging system. The image acquisition system saves the scanned digital image into a local storage device. It saves each image labelled with a sequence number. The size of each saved image is 4096 by 256 pixels. And the image merging system reads locally saved sub-images and generates a big extended image by concatenating small sub-images in order to refer to or diagnose crack width and/or spacing.

The image acquisition system described in Fig. 2 consists of two modules: control and management. The control module controls hardware devices such as the camera and storage devices. The management module takes charge of memory allocation and image saving. The control module has two parts: system control and disk control. The management module also consists of two different managing parts: file management and memory management.

The system control, one of the control modules, is responsible for CPU pre-emption of each process, memory consumption and the controlling of grabber, the image acquisition device. If a process preempts CPU resources too frequently, it will affect the overall system performance. Also, if the system performance worsens passing the threshold, previously captured images will be damaged or overwritten. To prohibit CPU pre-emption and protect the captured data, the system control

always checks the status of the system and pauses capturing if necessary. Now the disk control handles each storage device. The memory space required is enormous. Even if a tape storage device can give huge amount of storage capacity, it does not guarantee high-speed data transfer rate. Therefore the system uses magnetic disk storage devices instead of a tape disk. Our system has four magnetic disk storage devices. Each has 200GB of storage capacity. While the system is performing the capturing process, it will generate huge amount of images. Usually four IDE computer drives are provided in common personal computers (PC), so four magnetic storage devices are installed. In total, the system supports up to 1TB of disk storage capacity. The disk control manages each storage device in sequence and switches to other device if there is not enough free space in the current storage device.

The image acquisition is the most important part of the system. Whenever the linescan camera scans surfaces inside a tunnel, the scanned images in digitized format are saved into the main memory of the grabber board. To operate the image acquisition system in real-time, it directly saves the scanned images located in the grabber memory to the local magnetic storage devices. The file and memory management modules control each process and guarantee that the digitized image is safely saved into the storage device.

Fig. 3 shows the diagram of system management modules. Generally, the grabber board supports a mechanism of DMA (Direct Memory Access). With DMA, the scanned image in the grabber board can be directly copied to RAM in PC and then copied to the magnetic hard disk. However, saving images into a hard disk is much slower than copying between the grabber board and RAM in a PC. To manage or compensate for the speed difference, a buffer exists between two devices. The buffer is operated as a queue implemented as a linked list. When the images are

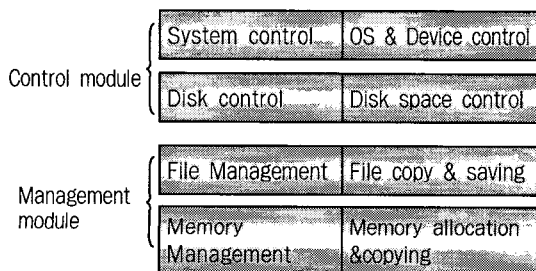


Fig. 2. System architecture of image acquisition system.

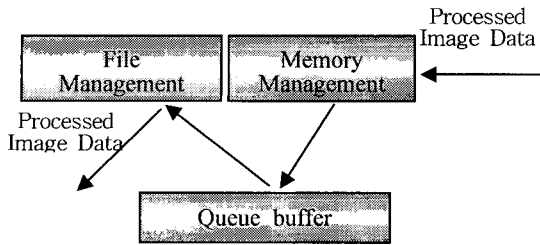


Fig. 3. System management.

copied from the grabber board, they are inserted to the queue buffer. The file management always monitors the incoming data in the queue buffer. When data is found in the queue buffer, it performs copy operation of saving the data into the local magnetic storage devices. And as soon as saving is completed the saved image is deleted from the queue buffer. In the first version of the system it is designed with a circular queue buffer with ten slots. Each slot can store 4096 by 256 pixel images. The circular queue works well independently but causes some problems in the environment in which multiple computer systems operate simultaneously. The reason is that if the system clock speed is not fast enough to process the file I/O or copy operation, the image data may be overlapped. A dynamically linked list is adapted to implement the queue. The dynamic list can be expanded or shortened dynamically depending on the amount of image data to be processed.

The file management saves the scanned image data into local storage devices. Standard I/O operations are adapted in our first version of the system. Despite the image saving procedure does not require much processing time, when the system is tested in laboratory experimental settings we have several problems such as a lot of system overhead, unwanted CPU pre-emption, an increase of queue buffer size and even system shut down. To make the system more reliable, it is modified to adopt the file caching method. Fig. 4 shows the system flow of the file caching.

The file caching method provides the mechanism through which the system reads data file

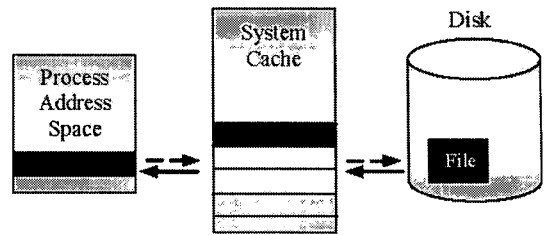


Fig. 4. Disk access using system cache(10).

from system cache area instead of reading from the physical disk. Correspondingly, it can write data to the system cache rather than to the disk. Originally caching occurs under the control of the cache manager that operates continuously while the operating system is running. Before performing the save operation, the file management creates an exact number of slot for the file by referencing the free space of local storage disk. If there is not much free space in the storage device, it switches to another physical device and creates a slot in the system cache. Then, the scanned image data is written to a slot in the system cache. The written data in the system cache is also written to the physical disk at given intervals determined by the operating system.

While saving image data to the local storage device, the file management creates sub-directories and maintains not to exceed a 1000 image data per each sub-directory. If more than 1000 images are allocated to the same directory, it may seriously degrade OS performance. The system always spends a lot of time by checking whether files with the same names exist or not.

3.4 Image merging system

All the scanned tunnel image data are saved in different sub-directories. Each slice image has 4096×256 pixels. The sliced images have to be merged into a large one for diagnosis of the inner surface of the tunnel. With the sliced image data, it is hard to measure the crack width and to judge the safety since a crack line might be divided and displayed in several consecutive slice images.

The image merging system also uses the file caching mechanism like the image acquisition system. Even though the image merging system does not require fast I/O access, the file caching is necessary for saving a large extended image without significant system delay. If the system uses the standard I/O operations to save the merged image data to storage device, it takes a lot of time and overhead. Therefore, to improve the speed of saving files, the system is designed to adapt to the file caching mechanism.

Fig. 5 shows the image acquisition system and the image merging system. Both images are taken in laboratory experimental settings. The image acquisition system shows currently scanned images and some useful information such as CPU and memory usages. Increasing CPU and memory (page file) usages can degrade system performance and cause system shut down. Therefore, the proper threshold has to be defined. If the CPU performance and memory size is above the defined threshold, the operation will be terminated automatically. The image merging system shows the merged image on the screen.

4. EXPERIMENTAL ENVIRONMENTS

The image acquisition system is tested in two different settings. First the system is tested in laboratory experimental settings.

As shown in Fig. 6, the rotational cylinder with two rigid columns is designed. The exterior wall of the cylinder is covered with line drawings. The

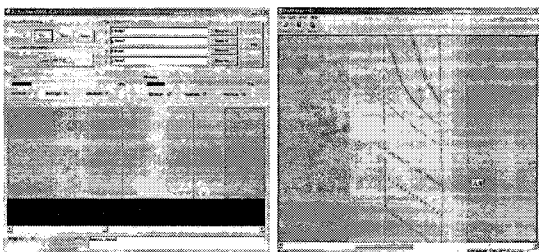


Fig. 5. Image acquisition system (left) and Image merging system (right).

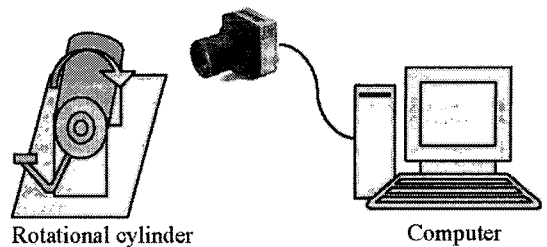


Fig. 6. Laboratory experimental settings.

lines are used to validate whether the data is correct or not. The system has been tested in two different computers. One is a 1.4Ghz, single CPU with a 512MB memory. The other is 2Ghz, Dual CPUs with a 1GB memory. In several initial experiments, the image acquisition system suffers from system lag during image capturing. Hence, the designed architecture of the system is modified to adopt some useful methods such as the file caching method and CPU performance and memory usage monitoring functions. Finally, the system works well even if the computer system has a low CPU clock speed. Also it never shows system lag.

After testing in laboratory experiments, the system is also tested in a real tunnel. The image acquisition system is mounted to a specially designed vehicle. The vehicle is designed like an electric motor and can be operated on either street or rail. Four computer systems with cameras are equipped to the vehicle to cover the tunnel's hemisphere-like shape seamlessly. Fig. 7 shows the vehicle equipped with cameras, located on the top of the vehicle and an image of the tunnel. The image has 4096×1024 pixels. Several scanned images (each having 4096×256) are merged using the image merging system.

5. A CRACK IMAGE RECOGNITION AND ANALYSIS SYSTEM

An image can be defined as a set of pixels the values of which represent brightness and coordinate values. The recognition of crack means to

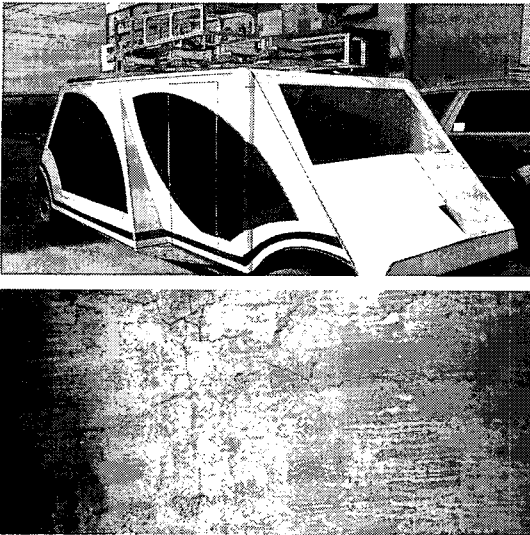


Fig. 7. Specially designed vehicle and Tunnel image (4096×1024).

find abnormal subsets of pixels within an entire image. In order to recognize a crack in an image, a specific pixel value is defined as a criterion by the expert and the value of cracks is compared with the predefined pixel value. When the value of the specific pixel is larger, it is considered as a crack and when the value is smaller, it is considered as a background and vice versa. This method is one of the oldest methods used in recognizing cracks in an image. Due to its inexpensive cost of calculation, it is the most common method in the world. However, if an entire image is composed of complicated sub-images, it is hardly possible to get a satisfactory result. For example, if the wall has multiple cracks, lots of stains and the wall image is obtained under inconsistent lightings, the separation among the cracks, the tunnel walls, and the background is very difficult. In order to measure the cracks effectively the process is divided into two stages, crack detection and crack measurement stages, as in Fig. 8.

5.1 Crack detection stage

The recognition of a crack in an image is accomplished in the crack detection stage. Crack

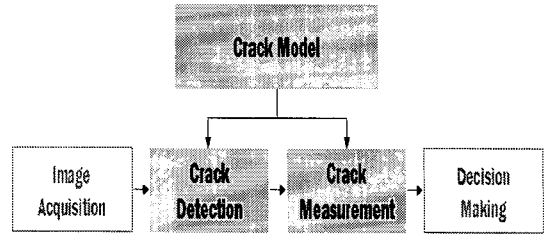


Fig. 8. Crack and damage detection and measurement stages.

analysis stage cannot be performed directly on the inner original tunnel image without proper manipulation since image distortions can often occur by the following reasons:

- Non-uniform lighting
- Spots caused by water leakage from the inner side
- Inconsistent inner structure of a tunnel
- Various noises caused by the environment

Fig. 9 and Fig. 10 show the difference between the images before and after contrast stretching is applied. Automatic crack detection may be ineffective. Since automatic crack detection requires searching the full image, it often requires considerably long search time. Therefore, we adopt the semi automatic detection process such that by

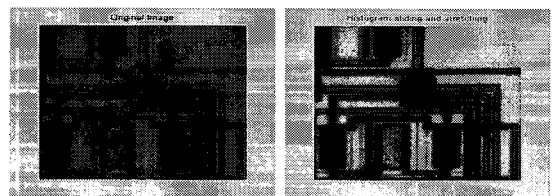


Fig. 9. Basis image and filtered image.

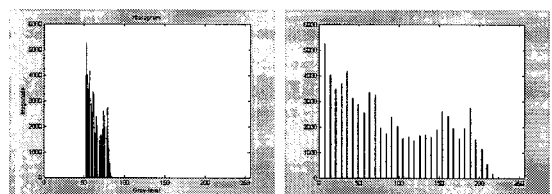


Fig. 10. Histogram of basis image and filtered image.

using a mouse, the user selects the crack by clicking on the beginning point and dragging to the destination point of the crack. Then, by the heuristic algorithm, the length from the starting point to the destination point called the distance can be obtained as well as the direction (central line of crack) of the crack.

5.2 Crack measurement stage

To obtain the crack acquisition in a tunnel image, various boundary detection algorithms such as Sobel, Template Matching, Laplacian Mask, etc. are applied. When a crack is relatively thick, all algorithms show satisfactory results. However, when a crack is relatively thin, all algorithms are not satisfactory. When applying Sobel algorithm, since too many pixels around the boundary are detected as the boundary, it causes to extend or reduce the crack boundaries abnormally. Template Matching algorithm also shows similar results, but it tends to detect a wider area as its boundary than the actual one. Laplacian Mask algorithm detects relevant boundaries regardless of the crack's thickness; however, since it is sensitive to noises, it may also produce many errors. Therefore, to improve the accuracy of crack recognition, a new method should be proposed.

Following the crack detection stage, the thickness of the detected crack is obtained in the crack measurement stage. Using the verified Daugman's iris recognition algorithm, the computation time and the accuracy of the thickness width of the crack can be improved. In this method, the change of accumulation value for a specific area of an image is analysed. The circular edge detector which was proposed by Daugman uses the maximum variation rate of the light intensity of a circumference that is defined as follows.

$$\max_{(r, \theta_0, \varphi_0)} \left| \frac{\partial}{\partial r} \int_0^{2\pi} \frac{I(r \cos \theta + x_0, r \sin \theta + y_0)}{2\pi r} d\theta \right| \quad (1)$$

The operator searches over the image domain (r, θ) for the maximum in the blurred partial derivative with respect to increasing radius r of the normalized contour integral of an image $I(r, \theta)$ along a circular arc of radius r and center coordinates (x_0, y_0) .

The proposed method adopts Daugman's method to apply in detecting a curved or a straight line by using a heuristic algorithm as in detecting the length and the direction (slope) of a crack. The thickness of the crack is estimated by averaging the width on the x -axis along the slope of every point on the center-line of the crack according to the pattern of a crack abstracted from a heuristic algorithm.

Equation (2) and (3) present the integrals w_{lefti} and w_{righti} of the values $I(m_x+x_i, m_y+y)$ of pixel at (x_i, y) from the crack center-line pixel at (m_i, m_y) along y -axis for $-p \leq x_i \leq 0$ and $0 \leq x_i \leq p$, respectively. The thickness of the crack is then estimated by the maximum values of the integrals w_{lefti} and w_{righti} obtained from equation (4) since the integral has a relatively large value at the edge of a crack.

$$w_{lefti} = \int_1^N I(m_x+x, m_y+y) dy, \quad (-p \leq x \leq 0) \quad (2)$$

$$w_{righti} = \int_1^N I(m_x+x, m_y+y) dy, \quad (0 \leq x \leq p) \quad (3)$$

$$\max(i, m_x, m_y) \left| \int_1^N I(m_x+i, m_y+y) dy \right| \quad (4)$$

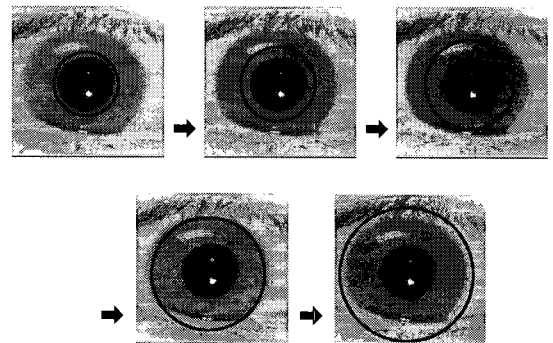


Fig. 11. Circular edge detection process that Daugman proposed.

Here, p is domain constant which is not fixed and varied arbitrarily by the user. Therefore, the increment of value p increases the calculations and decreases the speed of the system. In the case of a thin microscopic crack, the error rate of the thickness estimation increases due to noises as the value p increases. In this study, the speed of system is improved and the error rate is reduced by limiting the maximum thickness of a crack detected and cutting down unnecessary operations. Furthermore the options which the user can select as the domain constant p are fixed by 1mm, 3mm, 5mm, and 10mm, where both the width and the length of a pixel are set up to 1 mm. Fig. 12 shows distance between pixels from a centre one.

Results of the repetitive experiments of this study show that the error rate is bigger for cracks with uneven thicknesses and lengths larger than a specific one. To minimize error rate in the case of a long crack the length is divided into several cracks having up to 50 pixels, each thickness of which is estimated and then averaged. Fig. 13 shows system state of crack information that photograph to actuality tunnel reflex.

$\sqrt{2}$	1	$\sqrt{2}$
1	center	1
$\sqrt{2}$	1	$\sqrt{2}$

Fig. 12. Lengths between pixels from a centre.

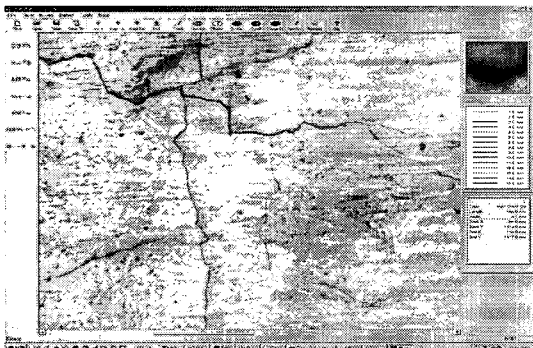


Fig. 13. Damage information abstraction software.

6. CONCLUSION AND FUTRUE WORKS

Diagnosing cracks in the tunnel plays a major role in deciding how safe the tunnel may be. Experts have usually diagnosed the tunnels through visual observation for several decades. Spending enormous amount of time in the dark, hazardous tunnels can cause physical ailments such as neck and eye injuries. Some researchers have designed various image scanning systems which enable experts to assess the condition of tunnels without physically being there. Although existing systems are efficient in taking tunnel images, it uses tapes as its storage devices or infrared cameras. The tape gives a large amount of storage capacity but cannot support real-time saving of image files. Also, infrared camera cannot present high-resolution images and therefore cannot be used in some countries including Korea since what the highest resolution infrared cameras can provide does not meet these countries' standards.

The system consists of two sub-systems, which are image acquisition and merging systems. The image acquisition system captures tunnel images in real time. Whenever the system captures the images, it saves the data to local storage devices. The image merging system is designed to generate a large extended tunnel image combining several small images. Diagnosing crack width and/or spacing efficiently from the captured data, it is possible to diagnose and validate the tunnel status. This system has been tested in field as well as in laboratory experimental settings. It is observed that the system works well even if the processing power is limited.

For future work we will improve the system by adding some filtering techniques to fix unknown errors. Even if the system is successfully tested in a real tunnel with a vehicle at the speed of 20km/h, it is not fast enough. Therefore, we should find another solution for taking tunnel images in high-speed mode.

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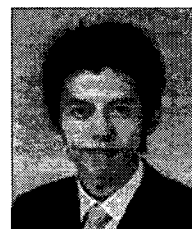
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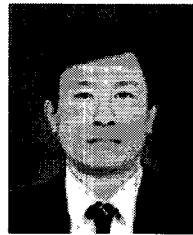


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