4. Development of Interactive Support System for Bridge Visual Inspection

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【Abstract】 A prototype of an interactive support system for bridge visual inspection has been developed. The aims of this system are to complement a technical knowledge of skilled inspectors and to suggest several alternatives concerned with decision-making at a bridge site. A multi-tier architecture that consists of a web server and a database server has been adopted in order to reduce client-terminals' load, to compute at a high speed, and to store and centralize a great amount of information. Open-source software packages were installed in the server and a web-application tied-up with a database system containing reports of bridge visual inspections was constructed. A wearable computer and a mobile communication device allow a hands-free operation and a seamless communication between the client and the server.

【Keywords】 bridge management, visual inspection, wearable computer, interactive support system, multi-tier architecture, web application, database, wireless communication

1. INTRODUCTION

In Japan, a large amount of infrastructure has been constructed in the last several decades, and its maintenance is becoming more and more important. The increasing maintenance cost will become a burden on the government and organizations that manage civil structures. In particular the increasing cost is becoming a crucial issue of local governments and small and medium-sized railway companies.

Among various tasks of infrastructure management, field inspection is essential in evaluating the current condition of a structure. Visual inspection is especially important to obtain critical information about the condition of the structure. Although recent development of structural monitoring can lead quantifiable and reliable diagnosis of structures, the decision of its installation depends on the current condition of the structure evaluated by visual inspection.

There are two major difficulties in visual inspection. One is that it requires much information on visual inspection while the other is that equipment that can be brought into site for the information reference and for recording is limited due to the nature of the field work. In bridge inspection, inspectors have to deal with many types of bridge in addition to the many factors that need to be considered, such as structure type, structure history, structure materials, load capacity, and its interaction with the surroundings, to name just a few. Regarding the equipment, it needs to be light and compact, because it is difficult to access some members and components even if ladders and a catwalk are available. If inadequate equipment is adopted, it not only disturbs inspectors' activities, but also increases the possibility of causing an accident.

In current practice, these difficulties are overcome by technical knowledge and experience of skilled inspectors. As a consequence of this practice, other problems arise. First, the ambiguity may occur by the inspector in the inspection result, and there is a room where the subjectivity goes into. Secondly, it is difficult to reproduce, generalize and inherit such knowledge and experience to other inspectors. Therefore, it takes much time and effort to improve

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the inspectors' skill and this situation limits the efficiency of the visual inspection.

In the U.S.A., each state has implemented a comprehensive bridge management system (BMS). Many states adopted PONTIS[1],[2] to optimize their bridges' management plans. This software package provides many useful functions. However, the tools that support bridge inspection are not included. In Japan, though the necessity has been recognized in recent years and some studies on BMS are being carried out[3],[4], little attention has been given to the improvement in efficiency and reliability of bridge inspection. Particularly, there has been no study attempting to feed back inspection records that are accumulated in a database to bridge inspection. On the other hand, Garrett and Smailagic have done the research[5] on developing a wearable computer for supporting bridge inspectors. In their paper, a wearable computer is mainly adopted as a recording device, the design of the system interface has been carried out, and it has indicated a possibility to develop a method to support the decision-making of an inspector.

In this study, a prototype of an interactive support system for visual inspection of bridges has been developed. The aims of this system are to complement the technical knowledge of skilled inspectors and to suggest several alternatives concerning decision-making on a bridge site. The characteristics of this study are described as follows. First, requirements for supporting visual inspectors are: improving efficiency by information support; improving reliability of visual inspection; removing differences among inspectors and subjectivity; providing appropriate tools on a bridge site. Second, requirements of the system being developed are: centralizing information; storing a great amount of information; reducing the client-terminal load; compatibility and implantability.

2. SUPPORT SYSTEM FOR VISUAL INSPECTION

2.1 Method of supporting visual inspection

In this study, an interactive support system for visual inspection of bridges has been developed. The system enables complementing a technical knowledge and the experience of skilled inspectors. The system has been designed to be used by inspectors who have already taken training courses to a certain extent and have less knowledge and experience than the skilled. However these inspectors are responsible for making their own decisions.

As a reference information, the visual inspection records of steel railway bridges that mainly serves the Shinkansen bullet train services were transferred to a database. Using the data, useful information is extracted from the enormous amount of information, and the support is carried out by sending the alternatives to inspectors when they makes their decision.

Methods of supporting visual inspection that are considered to be necessary are proposed as follows. The objects of the support are mainly divided in two, namely, how to find defects and what to do when defects are found. In the former, it is natural to make a checklist, however, if the list contains a large number of items, it takes a lot of time and effort, and the possibility of error is increased. Therefore, narrowing and prioritizing the list makes the inspection more effective. However, it is insufficient only to extract the inspection items, because the items will be scattered over the many parts of the bridge. Hence, the inspection route in which inspectors check the items has to be optimized.

Regarding the latter, what to do after defects are found, the support for inspectors' decision-making and the support for recording the inspection findings are useful. The decision-making support can improve the reliability and the efficiency of visual inspection by listing checkup items when defects are found. The efficiency improvement of the recording is also required, because it is difficult to make a detailed description of the inspection owing to the circumstances in the field. In this study, a function of listing the checkup items when defects are found is implemented into the prototype system.

2.1.1 Narrowing and prioritizing the inspection terms

To select a critical member whose failure would cause a portion of or the whole structure system to collapse must be carefully examined in every inspection. By carrying out the inspection according to the priority of critical members, it can save inspectors troublesome tasks and help to prevent overlooking fatal damages to a bridge. The conceptual method of extracting critical members is shown in Figure 1. This function consists of inspection records and an inference mechanism. From these records, items such as bridge type, design standard, age, etc. must be defined first. Then using these items, already-known facts and rules such as the relation between members and components, bridge type and design standard, construction date and materials, and so on are determined and implemented. Then, when inspectors want to know the critical members of the bridge being surveyed, they refer the support system by the condition or the property of the bridge. If there are any facts/rules that can be applied to, the support system replies several alternatives that indicate the location of critical members. Otherwise the inference mechanism produces the new facts using already-known facts/rules, then replies several alternatives. Referring to these alternatives, inspectors can now seek for the flaws of the bridge. Finally, the new rules must be verified by a report written by the inspectors who have received the support.

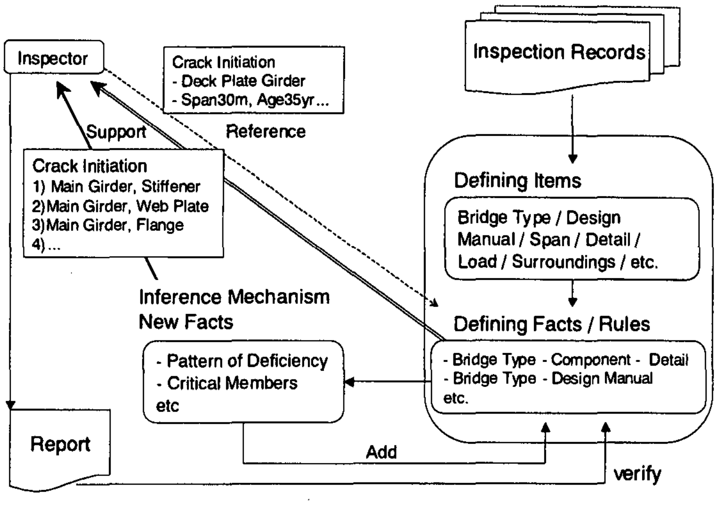

Figure 1: Identification of critical member

2.1.2 Optimizing the inspection route

The optimization of the inspection route is required in order to improve the efficiency of inspection. In this step, inspection items need to be accompanied with their locations in the bridge. The information to access members and components must be embedded in the support system. A problem that arises here is how to allocate inspection items (nodes) to the bridge as spatial data and how to evaluate the costs of links between these nodes. The costs of links are quantified in terms of time and effort to move from one inspection item to the other. If these nodes and the costs of links are specified, the problem results in an optimization problem in which the total cost of the route including all nodes is the object function that needs to be minimized.

2.1.3 Listing checkup items when defects are found

There are two ways how to make a checkup list: rule-based reasoning which is deduced from maintenance standards, inspector's manuals etc., and rule-based reasoning which is inferred from past inspection records. In this study, two ways of offering support information have been attempted. One is the list of the possible causes that are deduced from the inspection reports of similar defects to the ones being mentioned. The other is to show the criteria of AA-rank defects that are such urgent failures that some measures must be done immediately. Based on these criteria, the knowledge-base in Standard for Maintenance and Management of Structures was implanted in the prototype system.

2.1.4 Assistance in recording results of an inspection

When a defect is discovered, its description needs to be recorded. Among various methods of data entry, speech recognition and image pattern recognition reduce the cost of recording their findings drastically. Data entry by handwriting or using a keyboard is laborious in the field, therefore, when speech recognition becomes available, workability is rapidly improved. The same advantage is found using image recognition. It will certainly eliminate a sketch that inspectors need to describe the detail. The other useful data input is to store a motion picture. By recording a motion picture, the report can contain and represent more information about the details, crack opening under a live load, than comments that inspectors write down. Using pictures as data input also reduces the subjectivity of recordings, compared with comments written down by inspectors. However, speech and pictures as data input contain a lot of unnecessary information. An effective technique to extract useful information that makes these methods effective and practical should be developed.

2.2 Hardware

The prototype system consists of a server in which a database system and an inference system are constructed and a terminal that an inspector carries to a bridge site (Figure 2). The server and the client-terminal are connected through the Internet so that the cost and time of developing an interactive

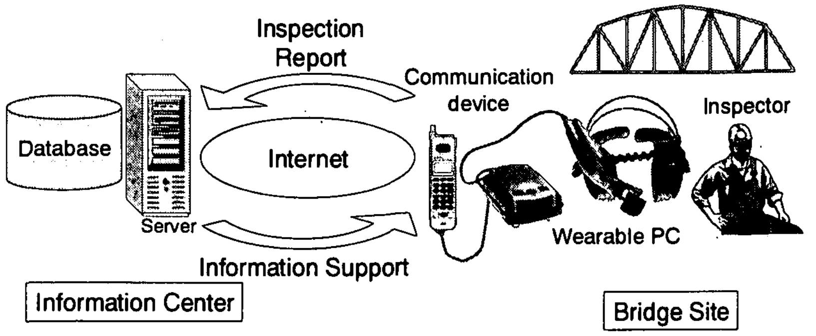

Figure 2: Web-based interactive system

system is saved. Inspection records are input from the inspector side, and support information is transmitted from the server side. Adopting the client/server architecture and the network at high transmission rate is to reduce client-terminals' load, to compute at high speed, and to store and centralize a great amount of information.

The specification of the PC adopted as the server is shown in Table 1. As a terminal in the inspector side, a wearable PC (Mobile Assistant IV™, Xybernaut® Co.) has been adopted, and its specifications are shown in Table 2. A wearable PC is by far the most portable of the mobile tools and makes possible the hands-free operation that is required in the field work.

Two types of cellular phone (PDC) and PHS (Personal Handyphone System) have been tested as a communication device between the wearable PC and the server. The transmission rate of a PDC is 9600bps and that of a PHS is 64/32kbps. These devices are connected to PCs through the PCMCIA card interface. DoPa is a communication service provided by NTT DoCoMo using packet-switched data transmission, and the transmission rate of 28.8kbps at a maximum speed is possible. The main issue now is to choose the appropriate device at a particular site depending on the service areas available.

2.3 Software

Figure 3 illustrates software to connect the server and the terminals. In Table 3, a list of software packages installed on the server is shown. By introducing these packages, the Web server undertakes the interface with the client side, and the client terminal needs only the Web browsing software. As a result, it is possible to construct a free environment at the client side. These packages installed on the server can run on many platforms that are compatible with UNIX. In addition, all application programs are written in Java language so that this support system is platform-independent.

Table 1: Specification of server

DELL DIMENSION XPS D300	
CPU	Pentium II 300MHz
RAM	64 MB
HDD	4 GB
NIC	3Com Fast EtherLink XL 10/100Mb TX
OS	Red Hat Linux 5.2 (JP)

Table 2: Specification of wearable PC

Mobile Assistant-IV™ (Xybernaut K.K.)	
-- HMD --	
VGA color monocular 640 X 480 resolution	
-- Processing Unit --	
CPU	Intel Pentium MMX 200MHz
RAM	32MB(on Board) + 64MB
HDD	2.1GB
OS	Windows98

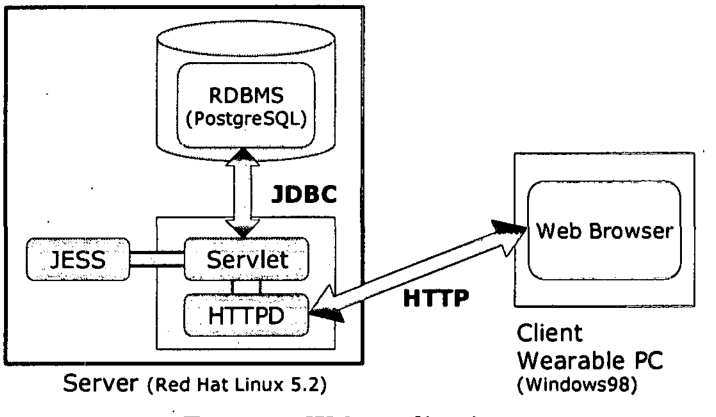

Figure 3: Web application

Table 3: Software package on server

Software Package	
RDBMS	PostgreSQL 6.4.2
HTTPD	Apache HTTPD Server 1.3.6
JDK	Java Development Kit 1.1.6
JSDK	Java Servlet Development Kit 2.0
Servlet Engine	Apache Jserv 1.0
Expert System Shell	Java Expert System Shell 5.0

PostgreSQL6.4.2 was installed as a Relational Data Base Management System (RDBMS) since several useful publications are available, and there are many reports of implementation of this package on the Web as its instructions. The details of the software is described in the following section. Apache HTTPD Server 1.3.6 serves as a Web server software. Java Development Kit 1.1.6, Java Servlet Development Kit

2.0 and Apache JServe 1.0 are also installed to operate Java Servlets on the server.

In this prototype, data retrieval applications and user interface are written in Java language. Java applications implemented in the network such as the Internet are divided into an applet and a servlet. An applet is triggered by a client's demand, sent from the server to a client and runs on a Java-enabled browser. A servlet is also triggered by a client's demand but runs on the server side and transmits the result to the client side through the browser. By implementing servlets, dynamic Web pages, server side includes, transaction by a form, URL redirection, HTTP Cookies and constructing multilevel model that consists of client/Web server/database or remote server can be available. However, these are also available by using CGI (Common Gateway Interface). Nevertheless, what makes a servlet be adopted is that it is excel CGI in some aspects. Though CGI runs a startup process every time it is accessed by a client, a servlet is made resident when Web server starts up. Therefore a servlet can process more quickly than CGI. In addition, a servlet has the additional advantage of imposing less load on memory and the sever than does CGI, since a servlet creates a thread and runs every time a request from a client is encountered, while CGI does not operate in a multithreaded way.

3. DATABASE FOR VISUAL INSPECTION

3.1 PostgreSQL

PostgreSQL, which is adopted in this study, supports the standard language for RDBMS SQL92 that was standardized in ISO in 1992. It supports almost all important functions defined in SQL92 such as transaction management, sub-enquery, a primary key, and has been reported to operate in many UNIX systems and UNIX compatible systems. Other advantageous features include that it can be used free of charge, and the entire source code has been made open to the public. Therefore, many developers have developed and fixed the bugs. Moreover a lot of information can be accessed from the Web. In addition, it supports various programming interfaces such as C, C++, Tcl/Tk, Perl and Java, and several interfaces such as PHP/FI and ruby are offered by third parties. It also contains JDBC for accessing by a program described in Java from the client. Beyond that client/server architecture has been adopted, and this software can be used with many languages.

3.2 Database structure

In this study, the visual inspection records of steel railway bridges that mainly serve the Shinkansen bullet train services were transferred to a database that is accessible from the Web. 920 bridge girders and 1280 reports of defect were stored into the database. The conceptual schema of the database is shown in Figure 4. It can be seen that tables are expressed in a frame of rectangular shape, their names are shown in the upper boxes, and their attributes are described in the lower ones. A line connecting these tables shows a relationship between them.

The database structure also features the standardization of terminologies of Bridge Type, Member, Components, Defect and so on in order to maintain the consistency of the data and in order to encourage sharing and reuse of the data. A combination of five items: Member; Component1; Component2; Component3; Defect is the core of an inspection report. Inspectors can easily store and retrieve the inspection records by selecting these 5 items. Also data administrators and managers can retrieve the records. These terminologies have respectively been registered on the database at each table. Only data administrators can carry out new registration, renewal and deletion on these tables. Inspectors only refer these tables and make inspection reports by choosing the items from these tables.

3.3 Information support by referring to the database

As for the reports in the database constructed, the bearing area is focused on and the causes of defects found at bearing area have been categorized since many defects were reported at bearing area. To categorize, first the groups of causes that consist of synonyms are defined, then, the groups of causes that are included by more than 2 reports are selected. As a result, 23 categories have been derived and the bellow is a list of selected categories.

- Unusual movement in the bearing
- Slippage of bearing
- Clearance of members
- Repeated application of train loads
- Subsidence of bearing

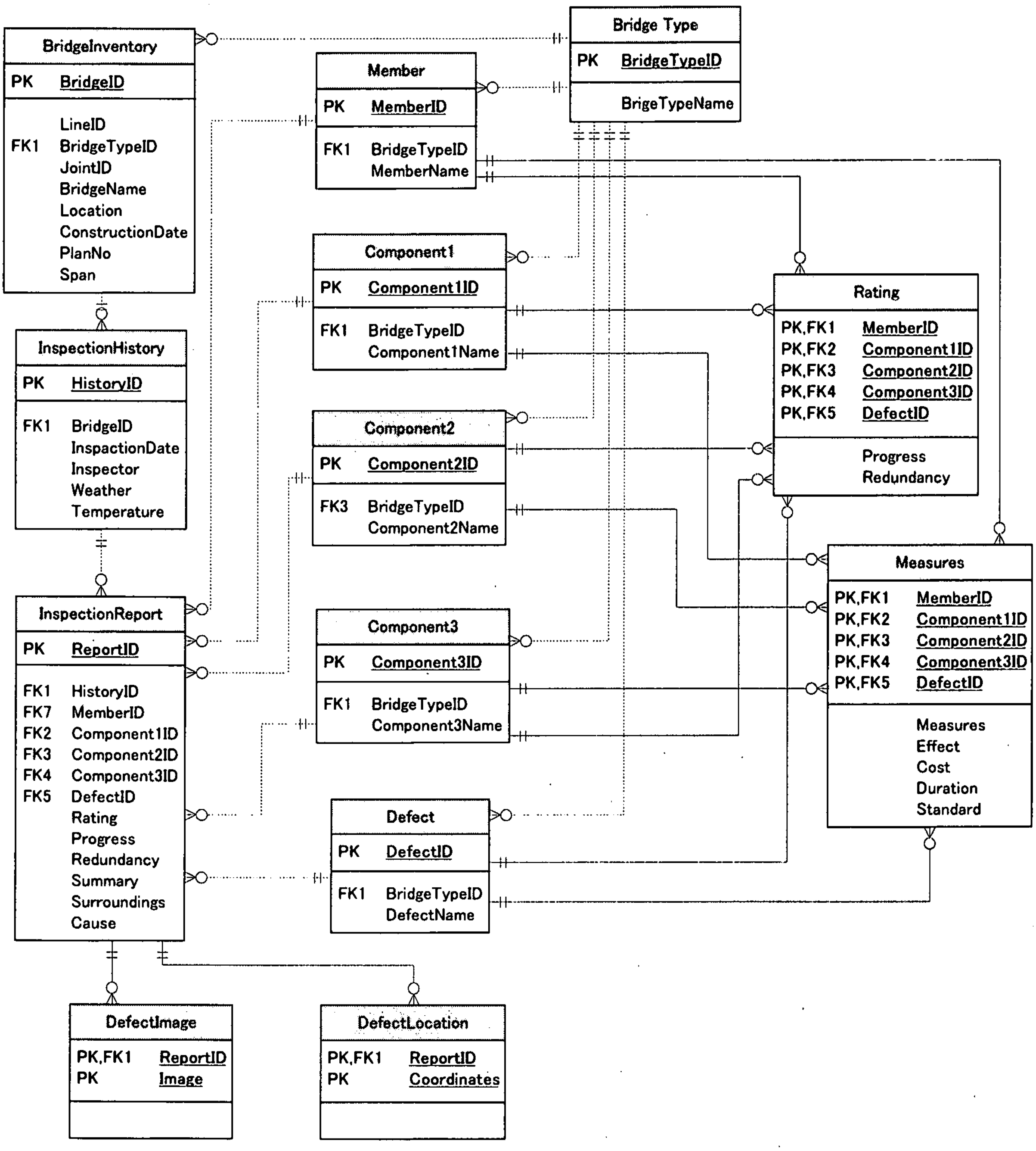

Figure 4: Data model

- Insufficient riveted connections
- Subsidence of steel pier
- Frozen bearing
- Dirt buildup
- Movement of girder

In Figure 5, a list of possible causes of a defect found at a shoe of a through-girder bridge is shown. The score shown in the bellow table is the number of categorized reports that consist of the same 5 items such as member, components 1-3 and defect, with the inspector's input data. Since this matching method is carried out regarding character strings, some inspection records match multiple categories. Therefore, the sum of scores is not always equal to the number of inspection records that consist of the same 5 items.

When the categorization is carried out as a manual operation, it takes too much time and effort, and the resultant number of records is impractical to process. In order to make use of database technology, every item needs to be stored as a categorized data or a numerical value. As a conventional method, reports are made by selecting categorized items that are defined beforehand. On the other hand, there exists a method in which so much attention has been paid recently. By developing data mining and text mining method, the data is categorized automatically and efficiently. If the former method is adopted, it will certainly take much time and effort to translate existing inspection reports into the database. Furthermore, the content that inspector' input is limited, and the handling of the input that has not been defined becomes a problem. Overcoming these drawbacks will require a new method of categorization and finding rules from the data efficiently.

4. INFORMATION SUPPORT BY IMPLEMENTING PRODUCTION RULE

4.1 Jess (Java Expert System Shell)

In this study, Jess (Java Expert System Shell) was adopted as a rule-based expert system that supports bridge inspectors. Jess is an open source software developed by Ernest Friedman-Hill at Sandia National Laboratories (http://herzberg.ca.sandia.gov/), and it is an expert system shell and scripting language. Jess has adopted OPS5 syntax, and carries out high-speed reasoning using the Rete algorithm. The code is entirely written in Sun Microsystem's Java to give itself some more advantages such as: Java functions can be called from Jess, Jess functions can be expanded by writing Java code, and Jess can be embedded in any Java application.

4.2 Method of information support

In this prototype, inspectors are supposed to receive useful tips from an expert system when they are trying to make inspection reports at a bridge site. These tips must be suitable for the situation in which the inspection is carried out. If the system maintain a large amount of information, offered tips must be selected; or the system may disturbs inspectors. An expert system can reasonably offer useful information in accordance with an inspector's inputs that describe the situation.

4.2.1 Criteria of AA-rank defects as a knowledge-base

The criteria of AA-rank defects, which are defined in Standard for Maintenance and Management of Structures (Draft) and Explanation, therefore[7] have been translated into production rules and implemented in the prototype. These defects are described as deficiencies or damages that can be found in general or regular inspections and that can threaten the service of trains and the safety of the passengers and the public in general. They are also

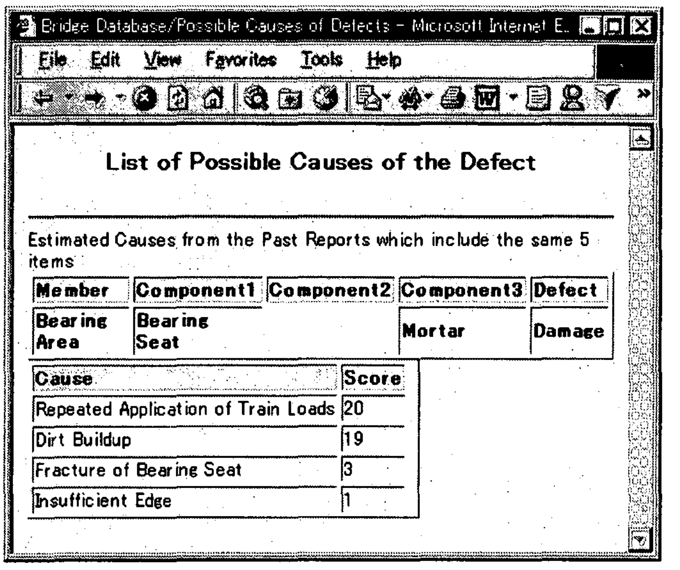

Figure 5: List of possible causes

described as critical damage that needs some immediate measures if they are found. The criteria of AA-rank defects are regulated as follows:

1. crack or fracture which cause a severe damage to functions of primary members;
2. considerable number of rivets or bolts of primary members' connections which have loosen, fractured or missed;
3. remarkable damages or subsidence at bearing area;
4. unusual displacement or deflection of structures;
5. defects threatening the operation of trains and the safety of the passengers and the public in general without immediate measures;
6. damages which may spoil the structure strength and serviceability when trains pass through.

For example, several criteria concerning bearing area damages described in the standard are shown in Table 4.

4.2.2 Implementation of knowledge-based system

In this prototype, when an inspector makes a report by inputting the defect's profile: member, components and description, the criterion of the possible AA-rank defect will be offered.

An example of rules that are described in Jess supporting OPS5 is shown in Figure 6. A rule is separated by the "=>" symbol. The LHS pattern that is shown before the symbol has six slots: Bridge Type, Member, Component1, Component2, Component3, and Defect. The RHS that is shown after the symbol means to display the criterion of an AA defect. As shown in Figure 4, inspection records consist of particular terminologies. Rules must be modified to be compatible with these terminologies. In RHS, a warning shows a possibility of an AA defect and its criteria, examples of which are listed the last column of Table 4, are described.

When an inspector finds a defect and submits a report, the system determines whether the defect is potentially AA-rank or not. The system inquires whether the attributes that an inspector input satisfy the LHS of each rule. If they satisfy, the system displays the possibility of an AA defect and its criterion. An example of the output result is shown in Figure 7. Input of "Through Girder, Bearing Area, Shoe and Damage", matches "remarkable damages or subsidence at bearing area" mentioned above, and "member fracture" is shown as the criterion of an AA-rank defect. It will now be possible to judge immediately by using this system whether the defect is AA-rank, when inspectors discover defects.

Although the method in which one input corresponds to one output is simple, it has revealed that it is possible to implement Jess into the system and to offer supporting information using production system. Further study on translating knowledge base by selecting rules from existing standards and manuals and on implementing technical knowledge and experience by interviewing skilled inspectors would significantly improve this support system.

5. EVALUATION OF THE PROTOTYPE

5.1 Inspectors hearing

An investigation was carried out in which inspectors tried to use a wearable PC and refer to the information in the database which is available on the Web site. A discussion about the support system that consists of a Web-application tied-up with a database system, a wearable PC and communication devices was held after the demonstration.

Place: Structures Inspection Center, Central Japan Railway Company
Date: Feb.2, 2000
Inspectors: Inspectors belong to Structures Inspection Center

There were many opinions and suggestions concerning the interface of the wearable PC. It was clear that the wearable PC was much more useful for field work than a laptop computer and a pen-based notebook computer in terms of the mobility. Some of the inspector hoped that they would adopt wearable PCs as tools for visual inspection, but others indicated it still had some problems to introduce into practical bridge inspections: it is bulky; it needs one

Table 4: AA defect of bearing area

Structure Type	Description	Criterion
All	crack of bearing surface	member fracture
Deck Girder, Composite	support settlement	more than 15mm
Through Girder, Truss	support settlement	more than 15mm

```
(defrule criterion of AA defect concerning ***)
   (Inspection Report (Bridge Type ***)
     (Member ***)
     (Component1 ***)
     (Component2 ***)
     (Component3 ***)
     (Defect ***))
   =>
   (print t "criterion of AA defect : ***"))
```

Figure 6: Example of implemented rules

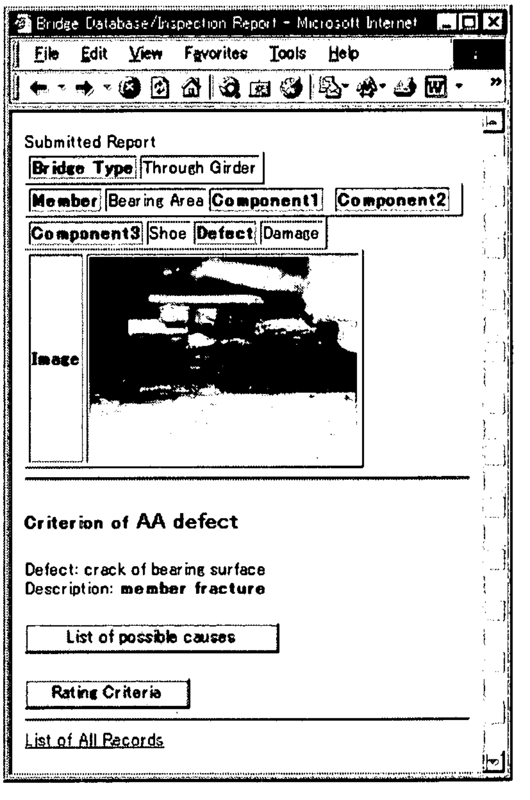

Figure 7: Criteria of AA defect

hand to operate its pointing device; it needs some practice to become accustomed to operate.

In the current version of the wearable PC, its user interface is very limited: a user has to operate its pointing device most of the time. Although optional mini-keyboard is available, it is awkward to use a keyboard at an actual bridge site. Most of the inspectors felt it difficult to point appropriate icons or menus by means of its pointing device.

Some inspectors suggested that if voice operation was implemented, the operation of a wearable PC would become much easier and the demand of wearable PCs would increase rapidly. If voice operation is put into practice, it will drastically reduce the effort to make inspection reports at the site.

5.2 Data transmission at a bridge site

5.2.1 Description

It was assumed that there was a damage of mortar in the bearing area. The inspection report registration was carried out in accordance with following procedures. A database reference whose method is described in Section 3.3 was also carried out, which invoked a list of possible defect causes stored in the database.

1. taking a picture using a CCD camera mounted on the HMD
2. sending an image file from client's Web browser to the server via the Internet
3. selecting items (bridge type, member, components and defect)
4. confirming the report

The image files were jpeg format (20-30KB) and DIB format (60-70KB), both are 320x240 pixels and 24bit color.

5.2.2 Evaluation of the wearable PC

Wearable PCs provide better mobility than laptop PCs and pen-based notebook PCs. Using wearable PCs in the field reduces the inconvenience of holding a PC during inspection. Furthermore, it is more useful in recording details, because of using the CCD camera that can be mounted on the HMD and can record still and motion pictures.

Two problems about the hardware were indicated. One was that it was difficult to see the display while inspectors were direct sunlight. Inspectors have to cover the display with their hands in order to view the content shown in the display, spoiling the mobility of the wearable PC. The other was that the wire that connects the HMD and the processing unit would slow down inspectors' activity in the field, particularly at a narrow space such as inside of a box girder of a small steel bridge.

5.2.3 Evaluation of wireless phone devices

PHS and DoPa were evaluated while the database reference that invokes a list of possible defect causes and that consists of text data was carried out. The difference between these two devices could not be recognized since data volume was very small (less than 10KB).

PHS needed 6-7 seconds for image transfer of a JPEG file, and DoPa needed 2-3 seconds. In case of a DIB file, these figures were 5-6 seconds for PHS and 10-15 second for DoPa, respectively. In both cases, it can be confirmed that the transmit rate will be practical without making user being frustrated if less than 100KB data is dealt with.

6. CONCLUSION

A prototype of an interactive support system for visual inspection of bridges has been developed. The aims of this system are to complement the technical knowledge of skilled inspectors and to suggest several alternatives concerning decision-making on a bridge site. A multi-tier architecture including a web server and a database server was adopted in order to reduce client-terminals' load, to compute at high speed, and to store and centralize a great amount of information. Open-source software packages were installed in the server and a Web-application tied-up with a database system containing reports of bridge visual inspections was constructed. Using a wearable computer and a mobile communication device allowed a hands-free operation and a seamless communication between the client and the server. The programs were written in Java that was designed to have as few implementation dependencies as possible. It enables the system to be platform-independent.

As a reference information for visual inspection, the visual inspection records of steel railway bridges which are mainly serving the Shinkansen bullet train services were transferred to a database which is accessible from the Web. Patterns of defect causes were determined to be available as the information support when using this database system. To complement a technical knowledge of skilled inspectors, the information about the criteria of AA-rank defects that are defined in Standard for Maintenance and Management of Structures was implemented into the system in a form of production rules.

A demonstration was carried out in order to confirm the effectiveness of the support system. As a result, some useful information about performance of the mobile communication devices and applicability of a wearable computer were obtained from this demonstration.

Further study on translating knowledge-based by selecting rules from existing standards and manuals and on implementing technical knowledge and experience by interviewing skilled inspectors is believed to improve this support system. Other useful methods to deal with a great amount of information efficiently such as data mining and text mining should be considered and developed.

It is clear that application of this method also benefits the acquisition of an inspector's skill when it is adopted as an education system.

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