Automatic Tunnel Monitoring System to Prevent Structural Failures & Collapses

Jung-Yeol Kim*, Soon-Wook Kwon*, Moon-Young Cho*

* Construction Engineering & Management Research Department, Korea Institute of Construction Technology, 2311, Daewha-Dong, Ilsan-Gu, Goyang-Si, Gyeonggi-Do, 411-712, Republic of Korea(e-mail : jrkim@kict.re.kr)

Abstract: Given the geographical characteristics and the national demand for sustainability, there is a strong need for tunnel construction in Korea. According to national highway construction statistics released by MOCT (Ministry of Construction and Transportation), tunnel s built after 1997 account for 54% of total number of tunnels. Up to now, measurement of position, pressure, force, torque, flow, magnetic field, temperature, humidity, gas composition, and liquid molecular concentration has relied on wired sensors regarding tunnel management. Such wired systems are exposed to many limitations in terms of accuracy of data communicati ons between sensors and main system. Therefore, a wireless automatic tunnel monitoring syste m is needed to facilitate construction and maintenance of tunnels and to ensure safety during such processes. MEMS (MicroElectroMechanical System) combined with RF(Radio Frequency)-based micro fabricated sensor which is one of the wireless sensing systems widely used medi cal and automotive industry can provide a potentially effective solution to monitor tunnel asses sment, crack detection, and tunnel construction monitoring. It has great potential in terms of applications to many areas of civil infrastructure systems along with standardization of data sensing, communication and analysis technologies. This paper presents a framework of automa tic monitoring system based on MEMS technology for on-going tunnel construction. Current application and analysis of conventional wired and MEMS based sensing technology will be included in this paper. This paper consists of sections describing: (1) Development framework of the automated tunnel sensing system (ATSS, Automated Tunnel Sensing System) (2) Analysis of current sensing methds for tunnel.

Keywords: Sensor, MEMS, Tunnel, TMS (Tunnel Management System), RF (Radio Frequency)

1. INTRODUCTION

1.1 Need for Systematic Data Acquisition

1.1.1 Construction

Regarding the national roads built and maintained by Ministry of Construction and Transportation (MOCT) in Korea, 54% of tunnels have been constructed after 1997 among all the tunnels built in the last 30 years for various reasons including environmental preservation. National highways tunnels are also on the rise, accounting for 66% of all the tunnels (as on May, 2003). However, as tunnel data monitoring is not standardized across the tunnels and measured data not managed systematically, such data is not utilized properly as basic inputs to tunnel maintenance activities.

Therefore, automation of civil structure data monitoring and systematic management of such data is required and automated, compact and wireless tunnel management system is necessary to meet the requirement.

1.1.2 Environment

Environmental concern has become the foremost factor to be considered in tunnel construction and maintenance. Notably, tunneling is one of the civil construction approaches to minimize environmental damages in mountainous regions. However, as indicated by the suspension of Sapae Mountain Tunnel construction regarding the Seoul Ring Way which incurred more than KRW 540 billion in loss, significant concerns are also raised against environmental impacts of tunnel itself.

Therefore, consideration of environmental factors during tunnel construction and maintenance is more critical than ever and it is necessary to manage environmental impacts of construction sewage, underground water leakage and exhaust emission, etc. to minimize damage to environment.

1.1.3 Maintenance

Tunnel data is measured in a limited scope for a short period of time or after cracks are detected, but, systematic data monitoring and management is required under the broader concept of Tunnel Management System (TMS).

1.2 Disadvantages of Wired Sensors

Sensors need to be utilized in a systematic manner to meet the aforementioned requirements, however, the conventional wired sensors are limited in itself in terms of installation and maintenance, exposed to more risks of damage and cost implications.

1.3 Objectives

To address the aforementioned tunnel monitoring system and sensors, two following research purposes are proposed regarding structural health for tunnels monitoring technology for structural failure prevention:

- Development of framework to combine conventional automatic sensors/RF-MEMS-based sensors & development of data management system;
- Development of framework for small wireless sensors and their applications based on RF(Radio Frequency)-MEMS(MicroElectroMechanical System) technology.

2. TUNNEL DATA MONITORING TO DATE

As for a sizable civil structure such as tunnel, management of monitored data required for construction and maintenance activities affect significantly efficiency of such activities.

Regarding tunnel data monitoring, Korea is on par with other countries as far as manual-monitoring technology is concerned, however, automatic monitoring of Korea is less developed when compared to other countries. Integral constituents of automatic monitoring technology are automatic monitoring management application and automatic monitoring sensors and imported products are used in most applications.

Table 1. Daily Data Measurement

Item	Description
Face Mapping	-Sheets, joints & fractures of face & exposed surface -Ground water leakage conditions & volume -Strain and defects of supports
Lining Strain Measurement	-Lining strain size, rate and convergence
Tunnel Arch Crown Subsidence Measurement	-Tunnel arch crown subsidence degree -Subsidence rate & convergence
Rock-bolt Pull-Out Test	-Adhesive strength of rock-bolts in place at different depth
Soil Subsidence Measurement	-Subsidence of soil over the crown of tunnel

Therefore, technologies applicable to tunnel maintenance are not properly utilized in many aspects in Korea as they should due to insufficient awareness of significance of tunnel maintenance up to now. In other countries, applicable technologies applicable to many aspects of tunnel monitoring have advanced to a significant degree, but, a system that can deliver integrated management functionality still seems in the making [1]. Following Table 1, Table 2 show recommendation on measurement items and their descriptions.

Table 2. Representative Data Measurement

Item	Description
Underground Strain Measurement	-Volume, rate and convergence of strain in semi circular area of rocks around tunnel
Rock-bolt Axial Force Measurement	-Axial force distribution, variation rate and convergence of rock-bolts in place
Shotcrete Stress Measurement	-Radial and tangential stresses, their variation rates and convergence of shotcrete in place
Underground Subsidence Measurement	-Degree of subsidence measured at tunnel floor at different depth

3. MEMS APPLICATION RESEARCH TREND

3.1 BiAST(Biaxial Strain Transducer)

BiAST is a biaxial strain sensing system applicable to rails developed by the University of Iowa based on MEMS technology[2]. The system was originally developed to monitor strain of aircraft structures, but, modified by the University of Iowa for application to rail. BiAST consists of Emitter beam, CMOS IC Chip, Connector, Sealed biaxial Mechanical flexure and Sensor base assembly, etc. integrated by MEMS technology. The system is installed at critical sensing spots to collect strain history data and identify rail fatigue conditions for maintenance.

3.2 MEMS-Based Accelerometers & Wireless Structural Monitoring System

This system was developed by the Stanford University and composed of MEMS-based accelerometers and wireless real time structural monitoring system module [3]. MEMS-based accelerometers measure acceleration based on variation of resistance in piezoresistor in reference to proof mass movement as described in Figure 1.

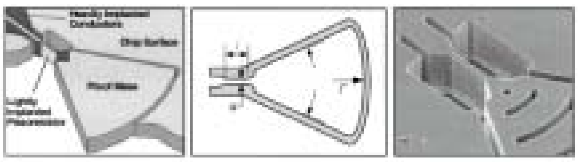

Figure 1. MEMS Based Accelerometer

4. RESEARCH RESULTS

4.1 Conceptual Design of Tunnel Monitoring System

Tunnel monitoring system consisted of conventional sensors and MEMB-based ones as described in Figure 2 is proposed to address the issues identified in the Introduction herein. In principle, the system monitors data wirelessly, whether the sensors used are conventional ones or MEMS-based ones. However, wired sensors can be used, depending on their application. Sensors are arranged per requirements of each work activity and data acquired in construction and maintenance phases is stored and managed by system. Data accumulated in the aforementioned manner can be applied to construction and maintenance activities.

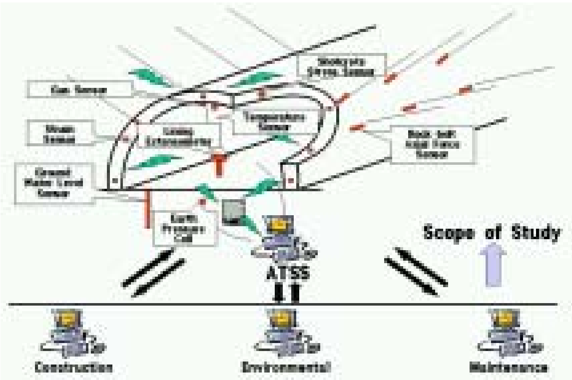

Figure 2. Concept of ATSS

As the system is a generic measurement and data management system, it can be applied to other civil structures such as bridges or dams, etc.

4.2 Selection of Target Activities

Tunnel monitoring can be divided into data measurement at in and out of tunnel body and tunnel body is broken down to tunnel body and inner tunnel parts (lining, floor and appurtenant).

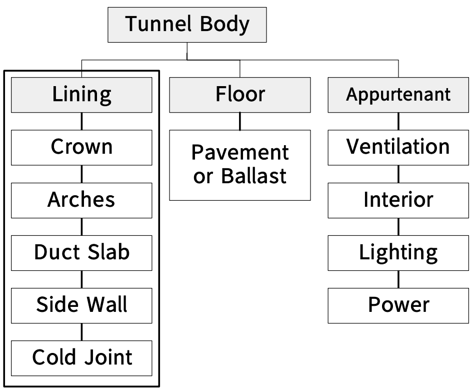

Figure 3. Targeted Activities

This research targeted crown, arch, duct, side wall and cold joints in consideration of ease of development and benefits as illustrated in Figure 3 in reference to recommendations of tunneling experts.

4.3 Development Methodology & Conceptual Design (Pending)

Referring to the achievement made by preceding researches and MEMS development methodology, development processes are proposed as described in following Figure 4. First of all, processes of the targeted activities were analyzed, required measurement items (strain or chloride etc.) were defined and targeted requirements of tunnel monitoring sensors were developed. Applicable technologies are selected as per targeted specification and subsequent processes follow in the order of design, analysis and simulation. If the design feasibility is verified in simulation, production process and mask design are defined to develop MEMS sensor.

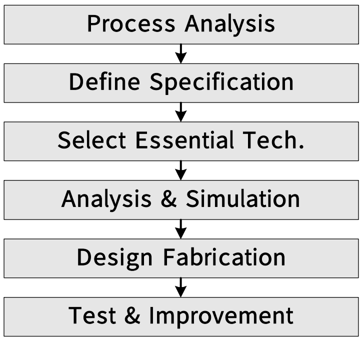

Figure 4. MEMS Development Methodology

Development of RF-MEMS sensor in accordance with the aforementioned processes require following consideration illustrated in Table 3. In development phase, sensor specification is defined in consideration of tunnel-specific environmental factors and appropriate material is selected. Regarding adoption of RF technology for wireless communication, decision should be made between passive and active types in consideration of service life of tunnel and efficiency of communication. Following sensor development, strain rate measurment spots or measured data collection interval must be determined and possibility of integrating various sensors in a single chip needs to be considered as well.

Conceptual design of MEMS sensors based on achievements made by researches available up to date is as described in Figure 5.

Table 3. RF-MEMS Sensor Development Consideration

Phase	Considerations
Development	- Tunnel-specific environmental factors - Spec.(strain rate measurement range, errors, etc.) - Selection of strain rate-measurement material
Wireless Communication	- Passive or Active (in consideration of service life of tunnel) - Maximum/optimum wireless communication-capable concrete depth
Application	- Selection of strain rate measurement spots - Strain direction measurement method - Measured data collection interval & method
Future Evolution	- Optimum combination of integratable sensors for strain rate, chloride, temperature and vibration, etc.

Sensors that can be most effective in application to tunnel body such as lining are strain rate sensors and its actuator is made from PZT most widely used and favorable in terms of its electrical and physical properties. Variation of resistance is received from actuator and data is transmitted to external antenna by Radio Frequency (RF) module after the resistance variation is analyzed. As the external antenna is more malleable than the actuator, it is expected to be safe from strain.

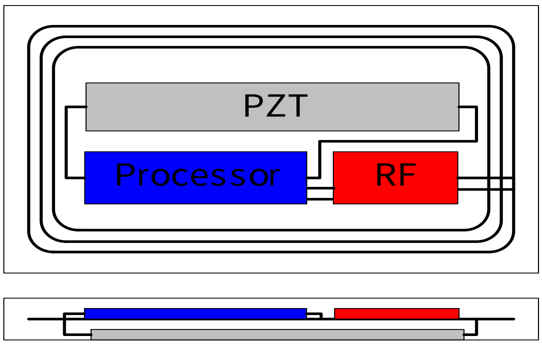

Figure 5. Concept Design of MEMS Sensor

5. CONCLUSION

ATSS targeted by this research can advance development of automatic monitoring and data management system applicable to tunnel construction, environmental preservation and maintenance and may support tunnel structure failure and advance safety planning. In addition, from economic and industrial perspectives, operation and maintenance costs are expected be saved as well as social costs since damages to civil structures can be addressed in advance, their service life extended and safety accidents prevented. Moreover, sensor markets will be expanded in the wake of MEMS sensor development and MEMS-based sensor makers will be able to advance into a market worth USD 5 billion in 2 years. Lastly, in terms of social implication, generic automatic monitoring and data management technologies can be applied to other civil structures (bridges or dams, etc.), resulting in mitigation of more safety hazards in construction industry as a whole.

REFERENCES

[1] MOCT, Development of Tunnel Maintenance System, Ministry of Construction Technology, 2000. 11

[2] M. Obadat et al., Full-Scale Field Evaluation of Microelectromechanical System-Based Biaxial Strain Transducer and Its Application in Fatigue Analysis, Journal of Aerospace Engineering, Vol.16, No.3, July 1, 2003. ©ASCE

[3] Jerome P. Lynch et al., Design of Piezoresistive MEMS-Based Accelerometer for Integration with Wireless Sensing Unit for Structural Monitoring, Journal of Aerospace Engineering, Vol16, No 3, July 1, 2003. ©ASCE