Research and Development of Road Infrastructure Monitoring Systems

Outline of Road Infrastructure Monitoring System (RIMS)

Features

◆24 hours monitoring by newly developed compact, low cost, and innovative sensors

◆Total maintenance of road infrastructure (bridge, road equipment and slope)

◆Applying to expressways and expanding to general roads

Background and Objectives

●Bridge :

■ "Aging" is serious problem

○43% of 16,112 bridges managed by NEXCO are older than 30 years.

<10years	10-20years	20-30years	30-40years	40-50years	50years<
10%	22%	25%	25%	16%	2%

○500,000 bridges (longer than 2m) are managed by municipality.

Administrator	Nation	Prefectures	Ordinance-designated cities	Cities, towns and villages	Expressway companies
Percentage	4%	19%	7%	68%	2%
Ave. age	35years	38years		35years	29years

○Close visual inspections is required once in 5 years for all bridge according to the uniform national standard.

■ Necessity of 24-hour low cost quantitative monitoring system for bridge damage

●Road Equipment :

■ Increase of the traffic volume

○Possibility of lack of life cycle of road equipment "on the bridge" due to the hard vibration

○1,000 equip. over 14,500 managed by NEXCO are on the bridge.

■ Necessity of 24-hour monitoring of unexpected load and deterioration

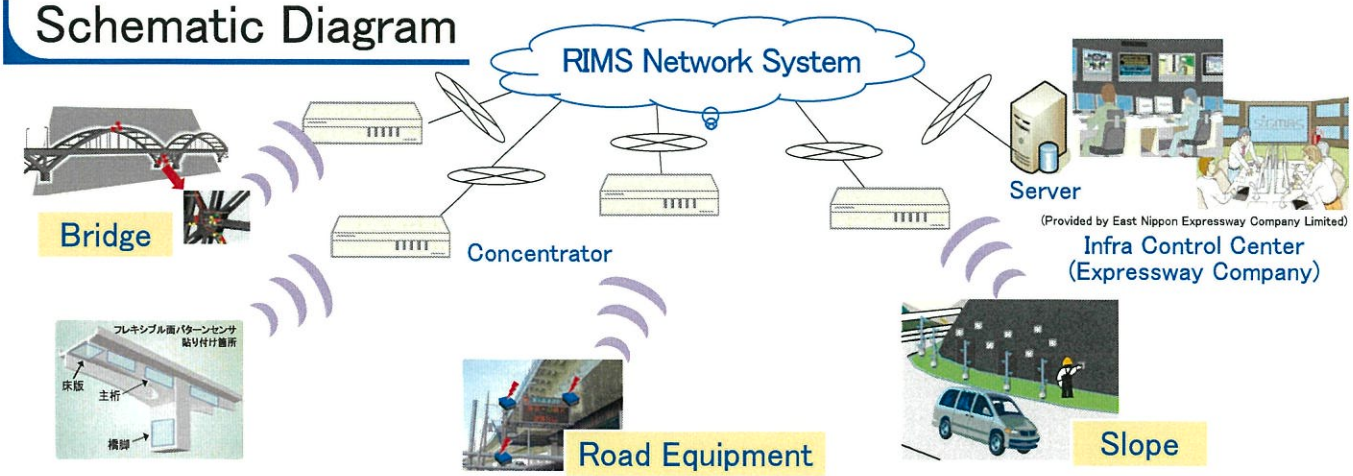
●Slope :

■ Number of slope in need of monitoring increased double in the past 10 years due to unpredictable cloudburst (guerrilla rainstorm)

○2500 slopes require caution and 117606 slopes need repair.

■ Necessity of 24-hour low cost monitoring system

Schematic Diagram



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Research and Development System of RIMS

Research & Development Scheme

(1)R&D of sensor terminals and monitoring systems

(1-1)Bridge

- (1-1-1)Super Acoustic Sensor (Vibration) (Toshiba,U.Tokyo,Kyoto U.)
- (1-1-2)2D-Strain-Pattern Sensor Sheet (Strain) (AIST,DNP)

(1-2)Road Equipment

- Tilt-Multi-Sensor (Fuji Electric)

(1-3)Slope

- Radio Wave Displacement Sensor (Mitsubishi Electric)

(2)R&D of the fundamental technology of sensing system

- (2-1) Common Platform for the Wireless & Secure Network (NTT-data)
- (2-2) Common Platform of the Highly Durable Packaging Technology (MMC,NGK,DNP)

(3)Common Platform of System Evaluation & Feasibility Study

(NEXCO East,Central,West,Hanshin Expressway,and Other members)

Research Organization

NEDO — Project Leader : Shin'ichi Yuta

Sub-project Leader : Isao Shimoyama

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Infrastructure Monitoring Laboratory

Satellite Laboratory

1. NTT DATA Corporation
2. Dai Nippon Printing Co., Ltd.
3. Toshiba Corporation
4. NGK INSULATORS, LTD.
5. Fuji Electric Co., Ltd.
6. MITSUBISHI ELECTRIC CORPORATION
7. East Nippon Expressway Company Limited(NEXCO East)
8. Central Nippon Expressway Company Limited(NEXCO Central)
9. West Nippon Expressway Company Limited(NEXCO West)
10. HANSHIN EXPRESSWAY Company Limited
11. National Institute of Advanced Industrial Science and Technology(AIST)
12. Micromachine Center

Project Promotion Committee (Quarterly)

Road Infrastructure Research Center

- Technology Work Shop (Monthly)
  - Common Platform WG (Non-periodical)

Headquarters

R&D Promotion Division

Committees

- Intellectual Property Rights Committee
  - Road Infrastructure Subcommittee

Re-entrustment : The University of Tokyo

Re-entrustment : Kyoto Unibersity

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Research and Development of Road Infrastructure Monitoring Systems

RIMS Today and Future

Schedule

●Project Period: 2014/7/3 ～ 2019/3/20

Theme	FY2014	FY2015	FY2016	FY2017	FY2018
(1) R&D of sensor terminals and monitoring systems					
(1-1) Bridge monitoring system using "Super Acoustic Sensor"(Vibration)	Completion of new monitoring system by 3 years →	→	→	Demonstration, evaluation and practical use study →	→
(1-2) Bridge monitoring system using 2D-Strain-Pattern Sensor Sheet (Strain)					
(1-3) Road equipment monitoring system using tilt-multi-sensor					
(1-4) Slope displacement monitoring system using radio wave sensor					
(2) R&D of the fundamental technology					
(2-1) Common platform for wireless communication network	Completion of common platform →	→	→	Evaluation and database construction →	→
(2-2) Common platform of the highly durable packaging technology					
(3) Demonstration and evaluation of RIMS	Preparation of demonstration →	→	→	Proof experiment and data accumulation →	→

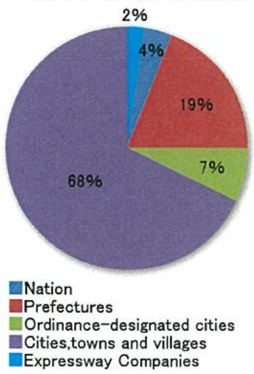
Future Works

◆Expansion to national road and local public entity management road

◆Expansion to other society infrastructure (Energy-related facilities, Railroad, Port facilities)

◆Overseas business development

The number of the facilities every road manager distinction



Energy-related facilities

Railroad

Port facilities

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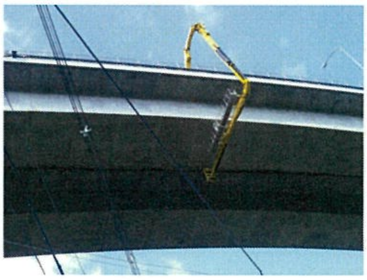
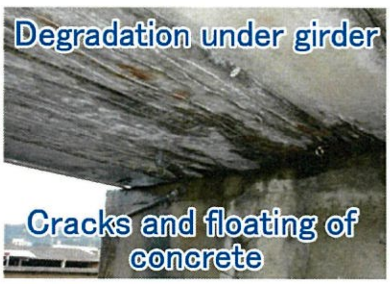
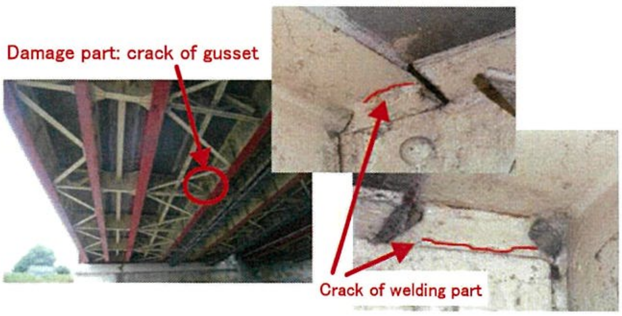
Bridge Inspection of the Expressway

Present Conventional Inspections

Visual inspection and hammering test from inspection passage	Visual inspection under the road	Inspection using high elevation work vehicle under the road
		
Inspection using high elevation work vehicle from main line	Inspection using bridge inspection vehicle from main line (1)	Inspection using bridge inspection vehicle from main line (2)
		

Examples of Degradation & Deformation





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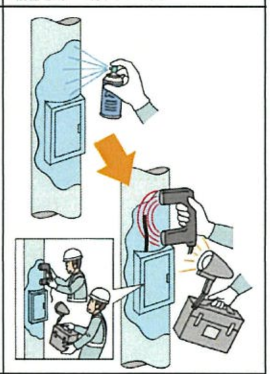
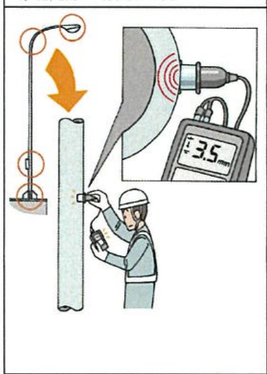
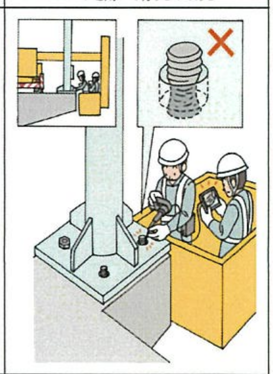
Inspection of Expressway Equipment

Present Conventional Inspections

Structural examination of tunnel ventilation facility

Structural examination of lighting facility

Visual inspection	Magnetic particle examination	Ultrasonic thickness measurement	Fiberscope measurement
◇道路照明設備の支柱、灯具の構造検査を、目視、触手、簡易な計器を用いて行うものである	◇道路照明設備の支柱の構造検査を、磁粉探傷器を用いて行うものである	◇道路照明設備の支柱の構造検査を、超音波厚さ計を用いて行うものである	◇道路照明設備の基礎の構造検査を、ファイバースコープを用いて行うものである
			
●支柱・基礎・灯具の発錆し腐食しやすい部分（ｱﾀﾞﾌﾟﾀｰ部、ﾒｶﾆｶﾙｼﾞｮｲﾝﾄ部、開口部、地際部等）の検査 ●ガタつき、損傷、腐食等を五感、ハンマー等で確認	●支柱の亀裂・損傷等が発生しやすい部分（ｱﾀﾞﾌﾟﾀｰ部、ﾒｶﾆｶﾙｼﾞｮｲﾝﾄ部、開口部、地際部等）の検査 ●磁粉探傷装置で亀裂・損傷等を検査（検査部にスプレーで磁粉を塗布し、ブラックライトをあてながら磁界を発生させる装置をあてがうと、亀裂等の溝がある場合はその部分が浮かび上がって見える）	●支柱の亀裂・損傷等が発生しやすい部分（ｱﾀﾞﾌﾟﾀｰ部、ﾒｶﾆｶﾙｼﾞｮｲﾝﾄ部、開口部、地際部等）の検査 ●超音波厚さ計で材料の厚さを検査（厚さが数値で表示される）	●地際部（アンカーボルト等）の検査 ●ファイバースコープでボルトの太さ等内部の欠損・腐食状況を検査

Detailed inspection manual ～（Example）Lighting facility of road ～

Examples of Degradation & Deformation

Corrosion of base metal

Corrosion and thinning of anchor bolt

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Demonstration and Evaluation of Road Infrastructure Monitoring Systems

Slope Inspection of the Expressway

Present Conventional Inspections

Visual inspection of ground anchor

Visual inspection from berm of slope

Visual inspection of excavation slope

Visual inspection of slope gradient

Visual inspection of embankment slope

Examples of Degradation & Deformation

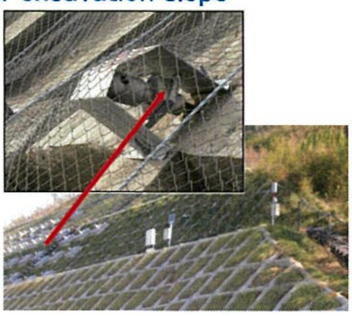
Fallen tree of excavation slope

Spring water from toe of slope

Sediment deposit in drain ditch

Crack and gap of concrete block structure

Projection of ground anchor of excavation slope



Slope protection subsidence

Slope collapse of embankment slope

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Development of Bridge Sensing System using Super Acoustic Sencor

Innovative Bridge Sensing System using Super Acoustic Sensor (1)

Features

◆New development of wide-band vibration sensor “Super Acoustic(SA) sensor”
◆Comprehensiveness of SA sensor to any stage of bridge degradation
◆Remote monitoring with palm-sized wireless sensing units

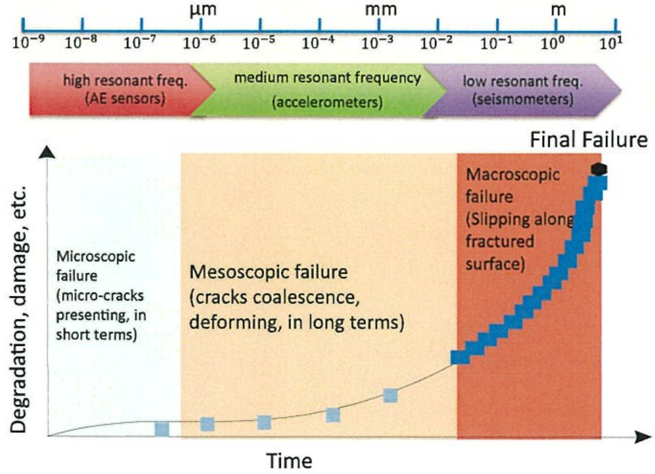
Background and Objectives

○A wide-band sensor from1 Hz to MHz order sensitivity are demanded in order to apply any degradation stage of bridges.

○To develop a sensor system with single sensor covering the following degradation stages :

From initial stage to initiation stage
(microscopic failure : 10kHz～1MHz)
Propagation to acceleration stage
(mesoscopic failure : several 100 Hz)
Deterioration stage
(macroscopic failure : several Hz)

Typical degradation pattern of Infrastructure



○SA sensors are expected to be applied to various materials such as soils, rocks, assembled structures, concrete, copper, composite materials, etc., and to various structures as well as bridges as a structure stethoscope.

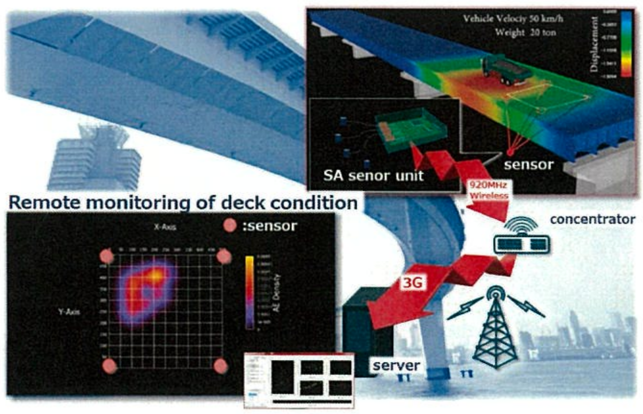
Schematic Diagram

○Basic concept of bridge sensing system with SA sensors

▶ SA sensor unit･･･Palm-sized, energy harvesting, wireless data transfer. Installation of any target point of bridges

▶ Wireless data correction from the sensor unit

▶ Remote sensing of the bridge degradation based on analysis results in a distant server



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Development of Bridge Sensing System using Super Acoustic Sencor

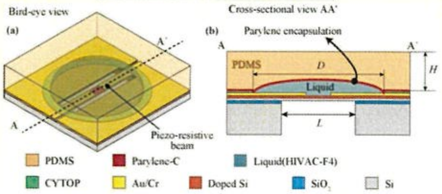
Innovative Bridge Sensing System using Super Acoustic Sensor (2)

Achievement (2014～)

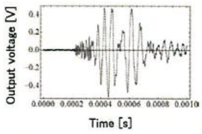
Outline of SA Sensor Device

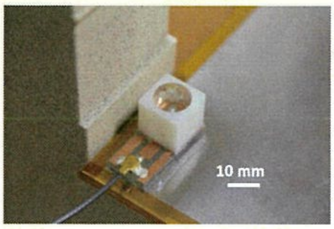
- Prototype of SA sensor developed. Wide-band response was obtained.

Structure of SA Sensor



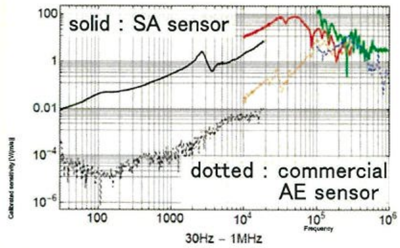
Measured waveform





Prototype

Frequency characteristics

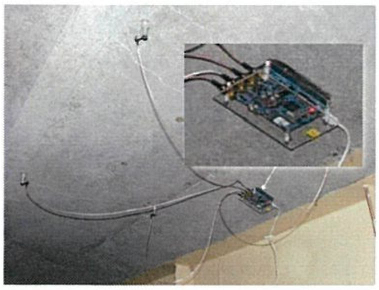


Development of Palm-sized Sensor Unit and Applicability Demonstration

- Achievement of energy harvesting, wireless and palm-sized unit

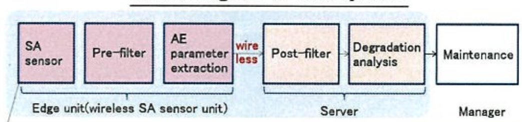
Wireless SA sensor unit

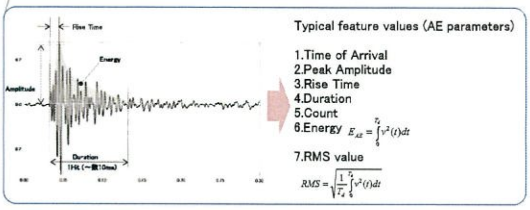
- Palm-size (100mm × 70mm)
- 4ch SA sensor connectivity
- FPGA for edge computation
- 920MHz-band wireless module
- Energy harvesting module



Attached sensor unit on surface of concrete deck

Block diagram of the system

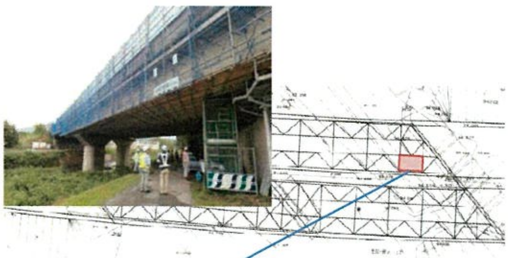




Quantitative Health Monitoring System for Bridge Structures

- Visualization of internal cracks in concrete bridge-deck by innovative method

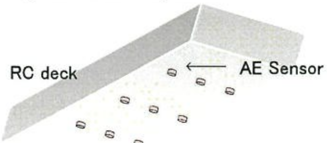
①Target bridge



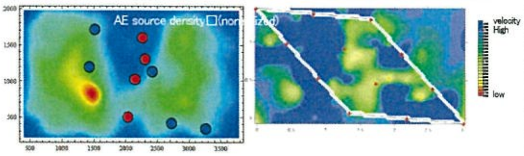
Severe cracks could not be observed although slight cracks were found.

②Sensor installation

Data from RC deck were collected by AE sensors system.

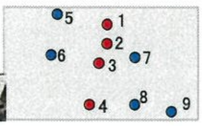


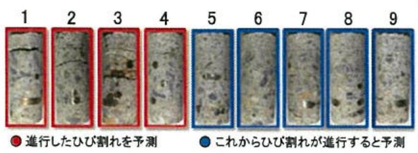
③Source location & velocity distribution analysis



The existence of internal cracks were detected based on AE source density and elastic wave velocity distribution.

④Validity confirmation





Internal cracks were successfully detected, which could not be aware by visual inspection.

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Flexible 2D-strain-pattern Sensor Sheet (1)

Features

◆Highly sensitive ultrathin silicon strain sensor array and low cost printed strain sensor array
◆Crack observation, detection, and prediction of steel bridge by 2D-strain-patern
◆Long time durability with UV-cut barrier layer and easy attachment by adhesive sheet

Background and Objectives

Crack on Steel Bridge :

■Formed near weld portion

○Visual inspection

→Crack search by magnetic particle flaw detection in case of confirmed coating crack near the weld portion

○Repair & Reinforcement

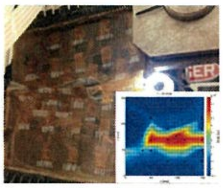
→Monitoring after stop hole perforation and/or welding

Crack near weld portion


Stop hole

Objective

Development of 2D strain sensor array for crack propagation detection


Crack detection by strain sensor array

2D Strain Sensor Array :

○Conventional strain sensor : Large power consumption, Difficult installation, Complex wiring

→Integration of piezoelectric MEMS strain sensor array on flexible substrate, Application by adhesive sheet, Wireless data transfer

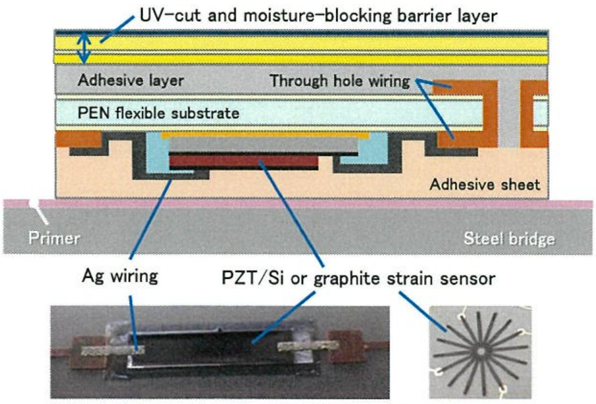
○Highway bridge : Dynamic strain derived from running automobiles

→Crack propagation detection by strain anomaly in 2D dynamic strain mapping

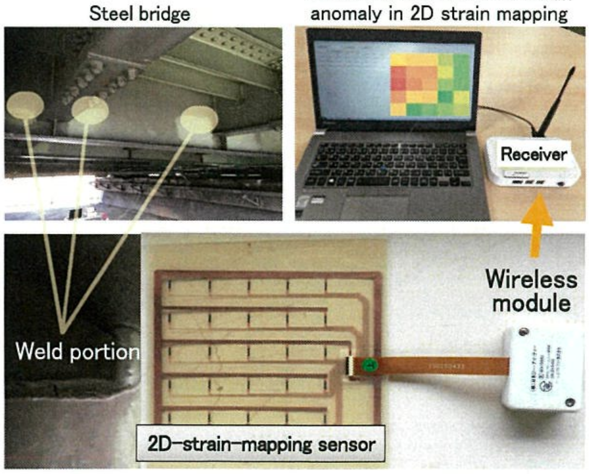
○Flexible substrates : Poor durability

→UV-cut and moisture-blocking barrier layer using organic/inorganic hybrid material

Schematic Diagram



Cross section of 2D-strain-mapping sensor



2D-strain-mapping sensor attached near weld portion

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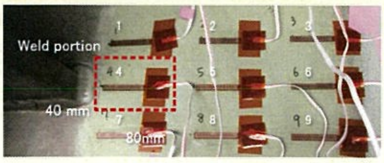
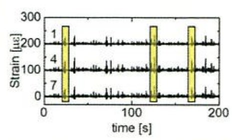
Development of Bridge Sensing System using 2D-strain-pattern Sensor Sheet

Flexible 2D-strain-pattern Sensor Sheet (2)

Achievement (2014 ~)

2D-strain-mapping of Steel Bridge





2D-strain-mapping (x10^{-6})

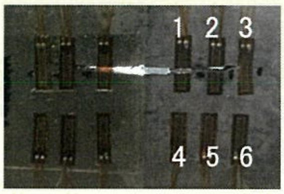
t=24s		
23	28	29
34	30	32
29	31	31

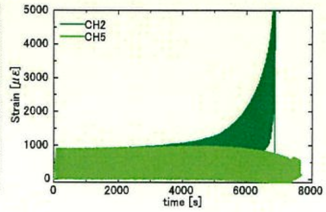
t=126s		
31	39	39
49	43	43
40	44	43

t=185s		
29	36	37
45	39	39
37	41	40

- 10~100 $\mu\varepsilon$ of dynamic strain by automobiles
- Strain depends on weight of automobiles, but 2D-strain-mapping is similar→stress concentration at weld portion

Strain Anomaly on Crack Propagation





2D-strain-mapping (x10^{-6})

1000s		
1200	900	800
700	900	800

3000s		
1900	900	800
600	900	800

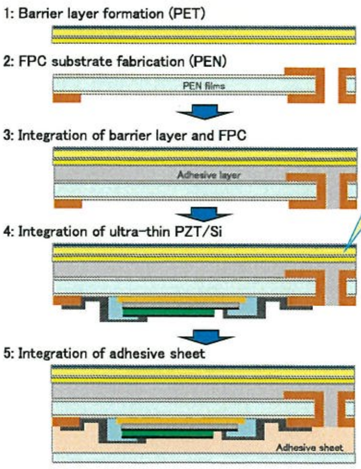
5000s		
3000	1000	800
500	800	800

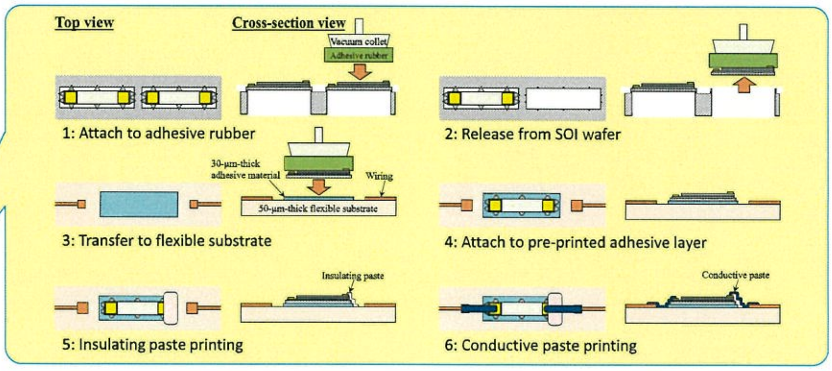
7000s		
3000	3000	1200
300	600	1100

- More than 1000$\mu\varepsilon$ of dynamic strain by crack formation

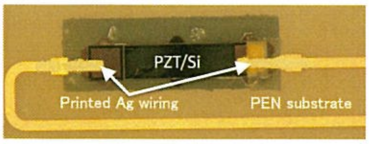
Fabrication Process of 2D-strain-mapping Sensor Sheet with PZT/Si Array

Integration of barrier layer, sensor array and adhesive sheet

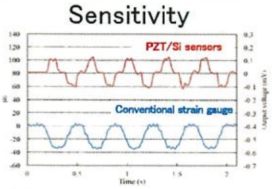




Ultra-thin PZT/Si



Sensitivity

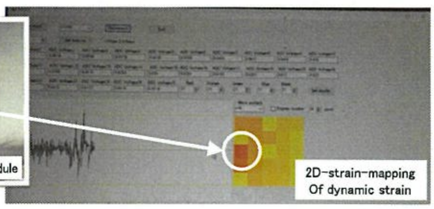


Sufficient sensitivity for dynamic strain of bridge

Installation of Sensor Sheet onto Steel Bridges

Easy installation onto steel bridge

Visualisation of stress concentration



Power consumption of Wireless module

Power	Active	Sleep
Amp, ADC	11.84mW	0mW
MCU, RFIC	111mW	0.037mW

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Road Information Board Monitoring using Tilt-multi-sensor (1)

Features

◆Tilt-multi-sensor using MEMS sensor device

◆Low power consumption and high speed wireless communication

◆Field trial on a expressway (actual field)

Background and Objectives

■Present issues of inspections : ageing of road equipment and shortage of technicians

○Increase in over 50 years old facilities in the next 20 years
Increase repair/renewal cost (Financial problems)

○Lack of maintenance technicians due to the declining birthrate and aging population (Human resource problem)

○Inspections are conducted visually, judgment is highly dependent on knowledge of technicians, experience and feeling

Current inspection (Image)

■Approach to issues : Improve inspection efficiency and quantification of judgement results

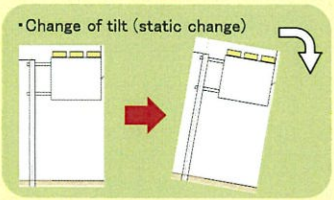
○Detect and quantify of structural changes and variations, and aim for support and efficiency improvement of inspection work based on quantitative results

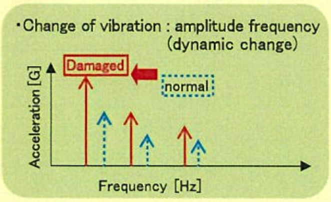
Sechmatic Diagram

Basic principle

- Corrosion reduction and cracks
- Looseness of bolt fastening part
- Variation of base or deformation during disaster

The source: Appendix (signs, lighting facilities, etc.) Inspection Procedure (draft) December 2010 Ministry of Land Infrastructure Transport and Tourism

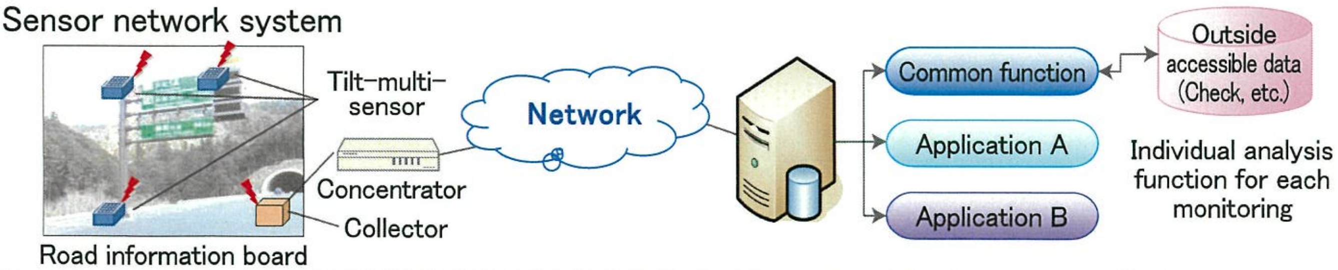




○Simultaneous sensing of static change (tilt) and dynamic change (vibration) of road equipment (information board etc.)
＊Development of tilt-multi-sensor

○Construct sensor network system and realize constant monitoring
＊Development of sensor network system

Sensor network system



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Road Information Board Monitoring using Tilt-multi-sensor (2)

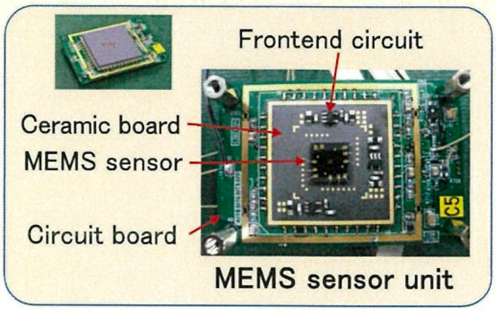
Achievement (2014 ～)

○Development of MEMS Sensor Device (Capacitive Acceleration Sensor Device)

Development target :

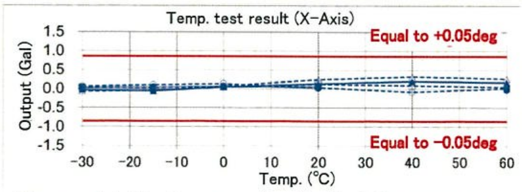
①Output stability of tilt measurement : 0.05deg (0.855Gal)

②Resolution of vibration measurement : 0.1Gal



<Results summary>

- Temperature stability 0.05 deg achieved with principle prototype
- Unit structured evaluation in progress



Temp. stability test result of principle prototype

○Development of Tilt-multi-sensor

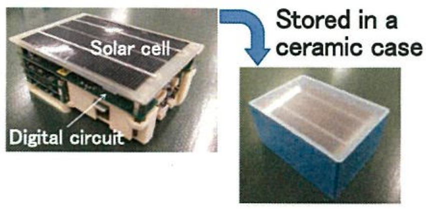
Development target :

①Concurrent measurement of tilt, vibration, and temperature

②Autonomous power supply by solar cell

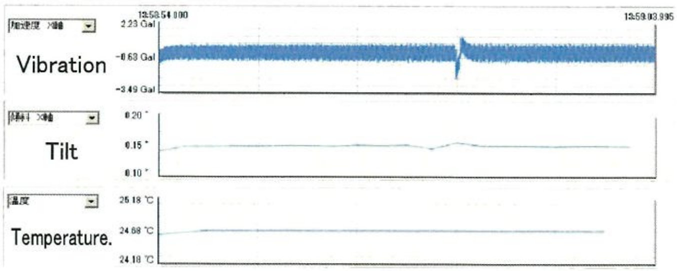
③Time synchronization (± 1 msec) between multiple sensors

④Wireless transmission of large amount of data (900kB/3min) with an average of 0.5 mW



<Results summary>

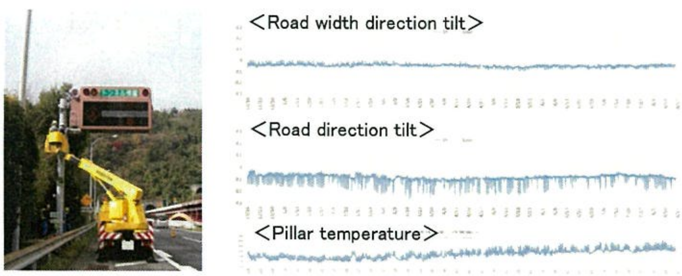
- Completion of structure design of sensor terminal and manufacture
- Concurrent measurement confirmation of tilt, vibration, and temperature
- Confirmation of wireless communication at real information board



Tilt-multi-sensor output example

○System Construction and Filed Test

- Preliminary field test (using existing sensors) Monitoring of tilt, vibration, and temperature with information board
- Development of the collector Design and production completed and operation test in progress



Azumayama tunnel entrance information board (2015.12.16～)

High Data Rate, All Weather, and 3D Slope Displacement Detection (1)

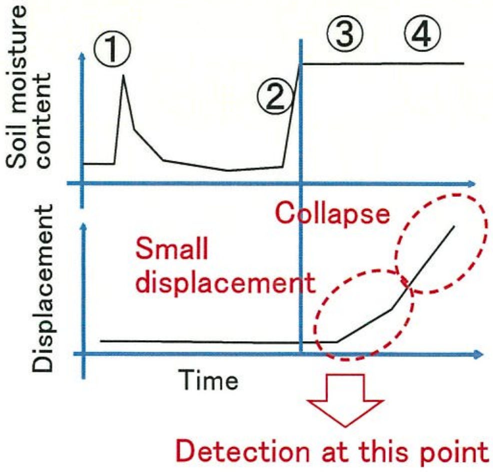
Features

- ◆All-weather, high-data rate, high-precision 3D displacement sensing using radio signal phase differences
- ◆Wide-area monitoring on a slope by a wireless mesh network
- ◆Long-lasting sensor device operating in all weather and day-and-night

Background and Objectives

Mechanism of Slope Collapse [1]

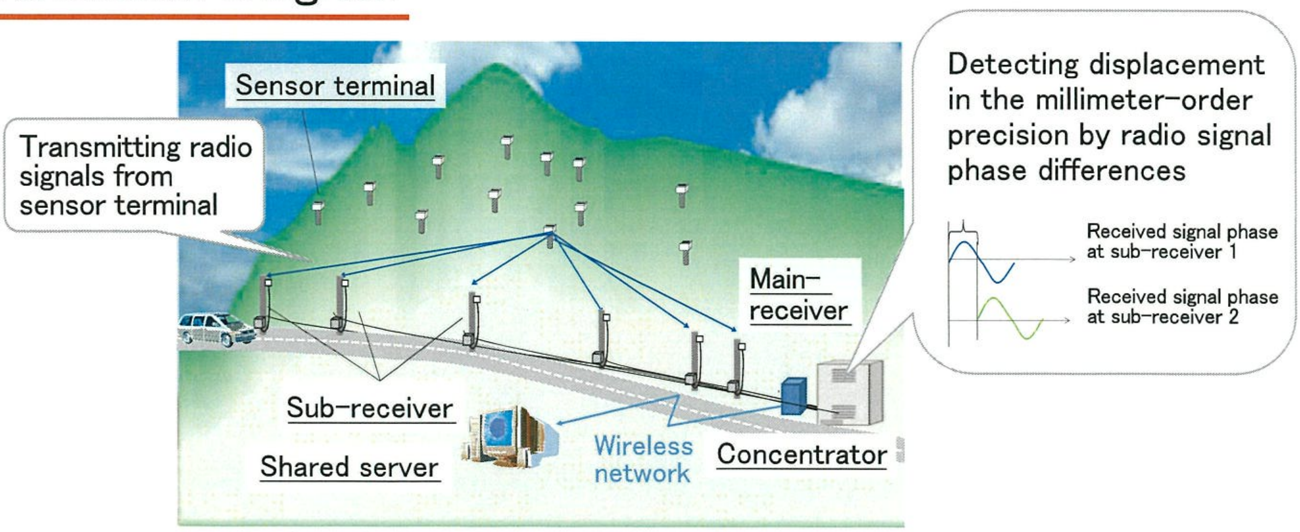
① Rainfall absorption into the ground
② Decreasing of soil shear strength
③ Occurrence of small displacement
④ Slope collapse



◆Assistance of earlier decision to close the road by detecting small displacement

[1]Koizumi et al., " Development of multipoint landslide disaster prediction system by wireless sensor net works(in Japanese)", Ministry of Land, Infrastructure, Transport and Tourism, National Land Technology Workshop, 2012

Schematic Diagram



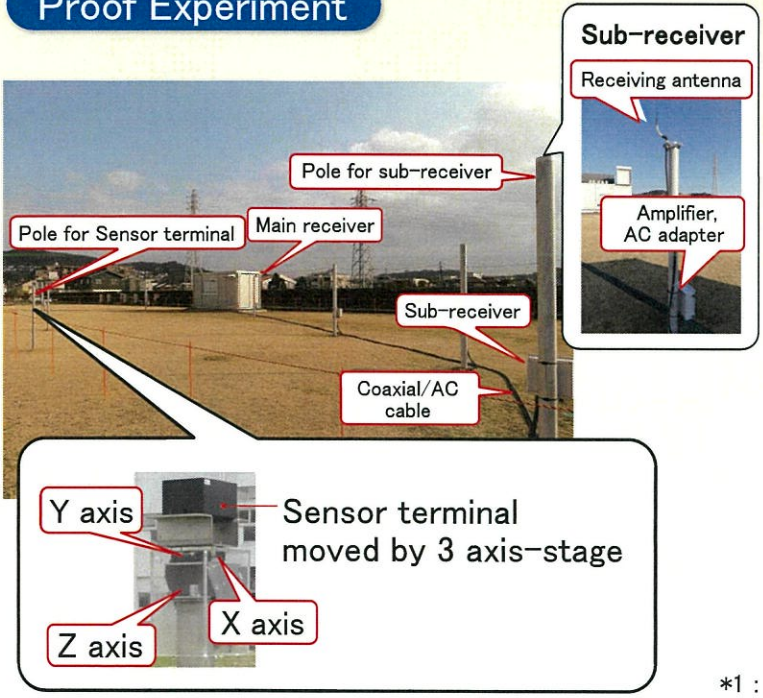
Outline of slope displacement sensing system

Development of Slope Displacement Sensing System

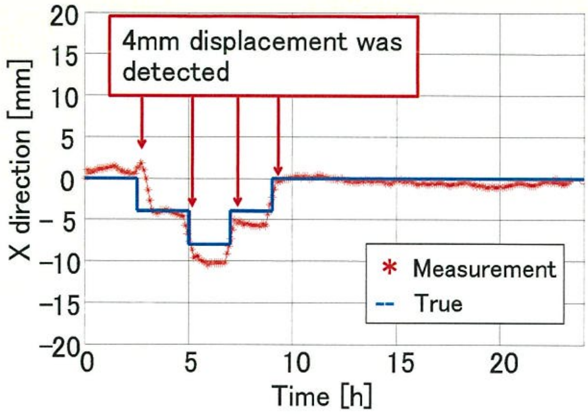
High Data Rate, All Weather, and 3D Slope Displacement Detection (2)

Achievement(2014～)

Proof Experiment



- 8 sub-receivers and 6 sensor terminals were located
- 4 mm*1 displacement was detected using 920MHz low power radio waves

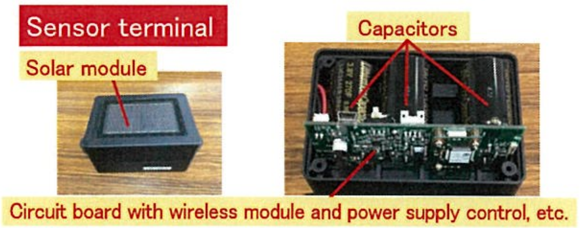


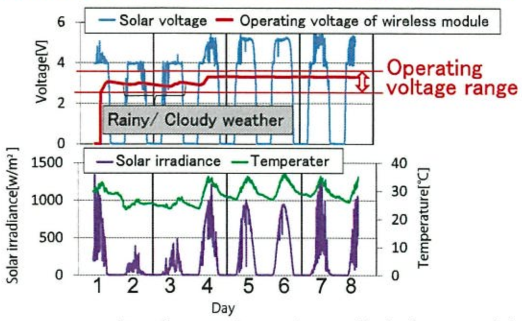
*1 : An example of control standard value for slope maintenance

Prototype of Terminal and Receivers

Sensor terminal

- Demonstrated continuous operation in rainy/cloudy weather

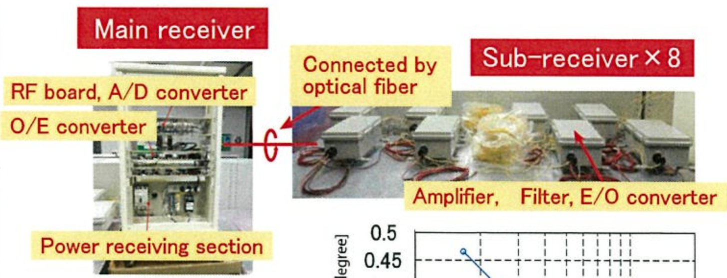




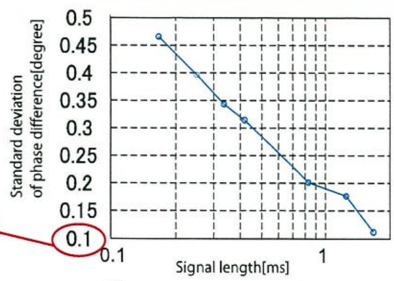
Measurement results of operating voltage of wireless module

Main / Sub-receiver

- Sufficient phase accuracy to achieve 4mm/h displacement in stand-alone unit



Sufficient phase accuracy of 0.1deg(≒0.1mm) in stand-alone unit



Phase measurement accuracy (2.5m distance between sensor terminal and sub-receiver)

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Development of Common Platform for Wireless Communication Network

Network Communications Infrastructure Corresponding to a Wide Variety of Sensors (1)

Features

◆Communication specification that absorbs various data formats and interface differences
◆Coordinated communication between concentrators, for easiness of installation and for cost reduction
◆Secure information gathering

Background and Objectives

■Due to the aging of road infrastructure and renewal of periodical inspection procedures, as various sensors are installed in road infrastructure, inefficiency due to duplication of communication infrastructure is a matter of concern.

○Inefficiency of data collection

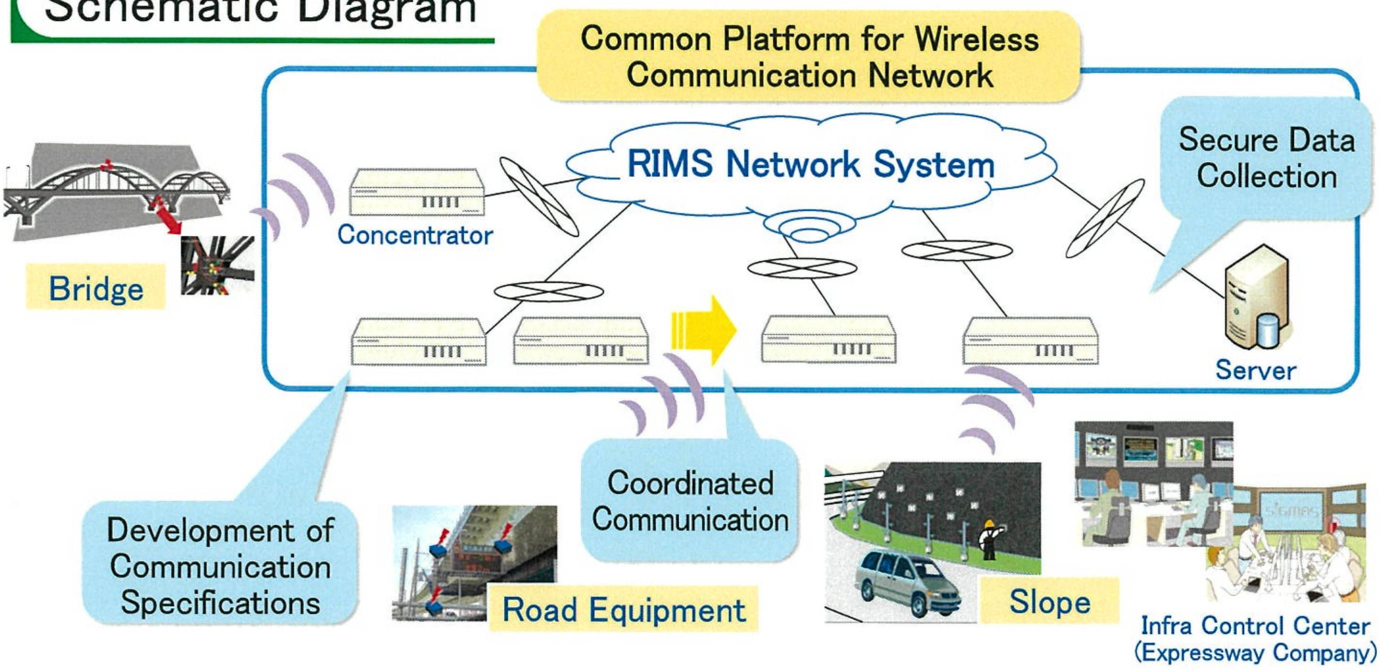
In conjunction with the development and spread of sensors and monitoring, it is necessary to build dedicated equipment and systems tailored to each unique method.

○Inefficient use of data

Because the commonality of data formats is poor, it is difficult to use data acquired from various sensors in an integrated manner.

There is a need for an open network communication infrastructure that supports a wide variety of sensors, manufacturers, and monitoring purposes. Absorption of differences is implemented mainly by developing communication specifications of concentrators.

Schematic Diagram



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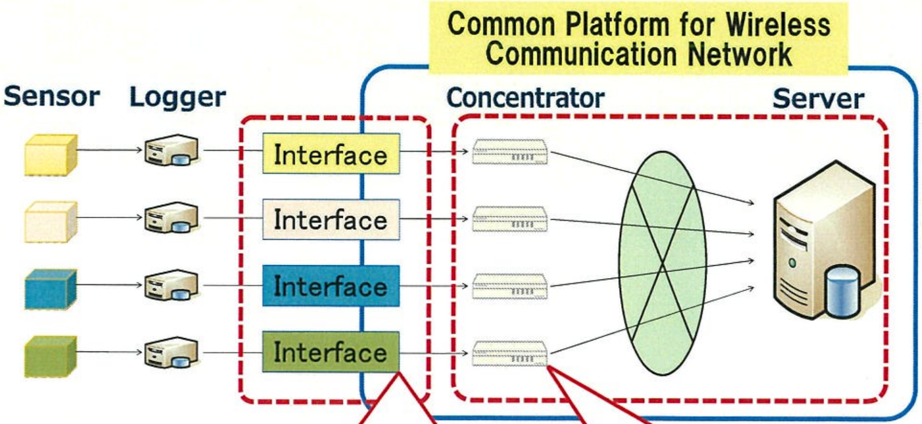
Development of Common Platform for Wireless Communication Network

Network Communications Infrastructure Corresponding to a Wide Variety of Sensors (2)

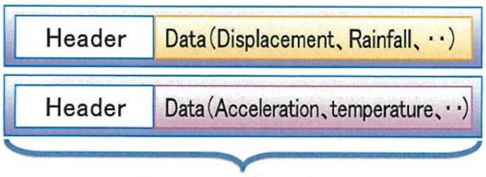
Achievement (2014～)

Development of Communication Specifications for a Wide Variety of Sensors

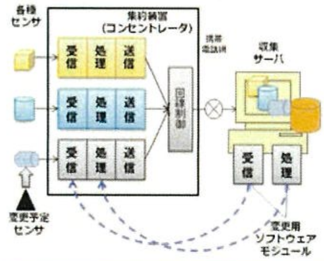
①Established data format and communication specification of each company based on common interface
Confirmed that there is no problem with the method by cooperation test
②Validated that receiving module can be changed independently and remotely



①Easy to deal with because it absorbs various data with a common interface

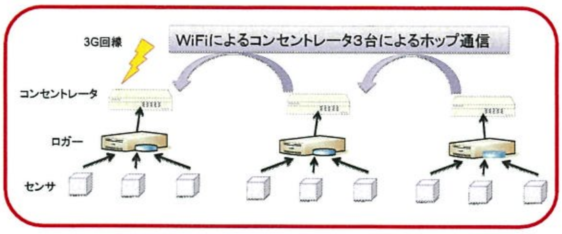


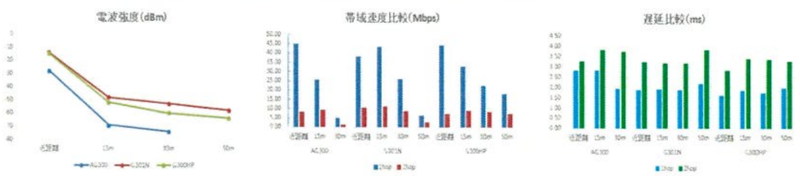
②Remote change of independent module



Coordinated Communication between Concentrators

A coordinated communication was confirmed up to 3 hops.





Secure Information Gathering

Communication by data proprietary encryption method, and remote change of internal module SSL communication method were implemented.
→Security verification planned for FY2016

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Robust Package for Environment Stress of Road Infrastructure (1)

Features

◆Packaging technology to guarantee monitoring in hash environment for a long time
◆All-in-one packaging with self-energy harvester, wireless module and sensors
◆Easy installation technology to structure with strong adhesion

Background and Objectives

●Higher Durability

■Environment of the sensor nodes

- More severe stress than indoor
- Need to guarantee the stable operation of sensing, signal processing and wireless communication even in anywhere
- Long life and high reliability request to sensor nodes from users such as NEXCO and Hanshin Expressway

↓

■Requirement

- 10 years guarantee in maintenance of function of sensors on road infrastructures where any severe environmental condition may happen

●All-in-one Packaging

■Providing to keep performance of terminals which include power generators, storage batteries, sensors, MPU, radio circuit modules

↓

■Ceramic packages must be able to protect all components of terminals from mechanical stress, electrical breakdown and to provide optical transparency, making good propagation of characteristic in electromagnetic wave and vibration.

●Easy Installation

■Requesting workability and maintenance as well as strong bonding to structures

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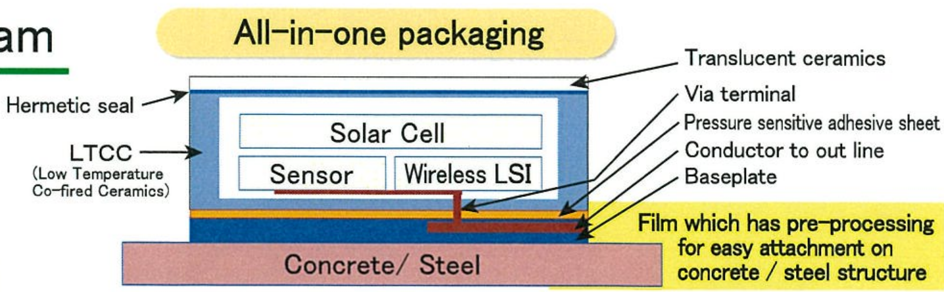
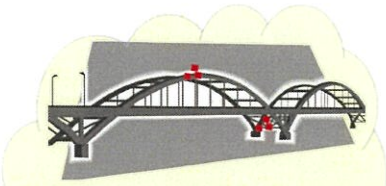
■Direct bonding sheets including sensors to concrete/steel structures

Schematic Diagram

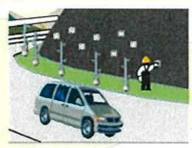




High concentration of brine, Lightning strike, Rainstorm

Environmental stress of road infrastructure

Lightning strike, Rainstorm, High level corrosion gas, Strong vibration



Heavy snow, Rainstorm, High and low temperature

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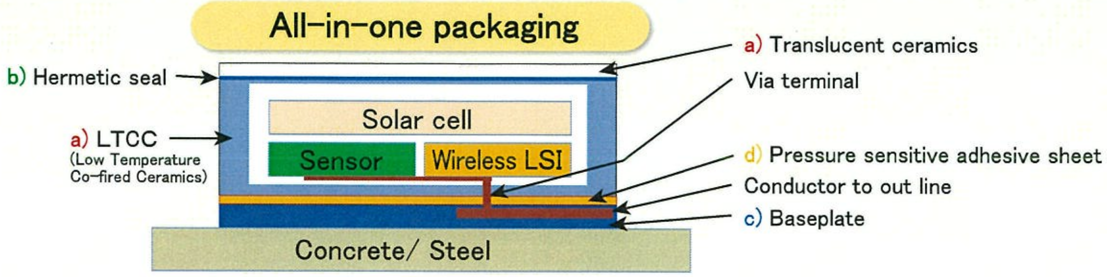
Robust Package for Environment Stress of Road Infrastructure (2)

Achievement(2014 ～)

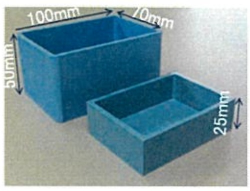
Final Goal

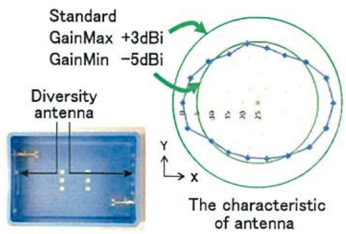
The Size of Package : 7cmx10cmx5cm　Durability : 10 years or more



a) Upsizing technology of LTCC substrate within antenna and translucent ceramic substrate (NGK)

- Upsizing to the size of 7cmx10cmx5cm, prototyping of LTCC substrates with diversity antenna for low directivity

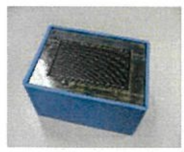




The characteristic of antenna

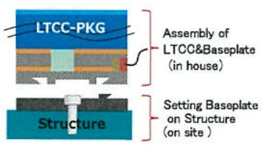
b) Hermetic sealing technology to use low temperature bonding material (MMC)

- Developed hybrid material mixed inorganic-organic, and also developed hermetic sealing technology to bond translucent ceramic substrate on LTCC with low temperature. To meet the standard of Weathering test(500 Hr), PCT (Pressure Cooker Test) and Heat Cycle test (−40℃⇔85℃, 200 cycles)



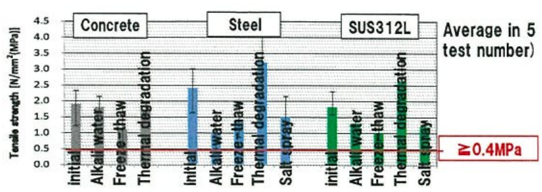
c) Designed and prototyped the baseplate for easy attachment on concrete / steel structure (DNP)

- Baseplate Material->SUS312L



d) Developed direct bonding technology to use original epoxy resin sheets (DNP)

- Passed durability acceleration test (JISA5557) in the condition of severity of 1.5 times to use test pieces of Concrete, Steel, SUS312 Tensile strength is more than 0.4 MPa



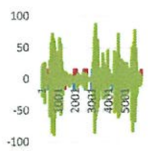
Tensile strength test result

e) Developed remote evaluation test method (MMC, AIST)

- Durability acceleration test results can be acquired from remote areas. Can be used for the site test such as Houenzaka Bridge of Hanshin Expressway, Nishiandobashi Bridge of West Nippon Expressway.

Nisiandobasi Bridge

Tranceiver system



Vibration Data in Server