# An Application of Industrial Agents to Concrete Bridge Monitoring

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Abstract: Bridges are key elements of transportation infrastructure. Being expensive vital infrastructure, continuous monitoring and preventive maintenance are of the essence. Wireless sensor networks, the technology of the 21st century offers promising features for a wide range of applications including civil infrastructure monitoring. We present an application of sensor networks backed by agent technology and ubiquitous computing all merged in a holarchy for bridge monitoring. The overall system architecture, context ontology, sensors required, decision support system and agent architecture are presented.

## 1. INTRODUCTION

TRANSPORTATION infrastructure has emerged as one of the main economic indicators of nations prosperity. Bridges are key infrastructures in the transportation system. The strategic location of bridges in the transportation system further enhances their value. Bridges are expensive structures and hence it is very important to maintain and repair them on a continuous basis for cost and safety purpose. There are almost six hundred thousand bridges in the United States out of which 27 percent are rated as structurally deficient or functionally obsolete. 188 billion dollars would be required in the next 20 years to eliminate bridge deficiencies (Asce, 2005).

Three main problems that deteriorate bridge decks are cracking, delamination and corrosion. Once a bridge is affected by one of the aforementioned problems, it can always lead to more serious structural defects.

Monitoring is one of the most important components in any repair and rehabilitation project of a concrete bridge. The traditional way to bridge monitoring is through personal survey by a bridge engineer. Based on the information collected from survey data and past professional experience, the bridge engineer decides the repair strategy. Inadequate survey was one of the causes in the collapse of several bridges, among which are Silver Bridge, Ashtabula Bridge, and Mainus River Bridge (Bridge, 2005)

The latest advances in distributed computing and microminiaturization has enabled in the past few years the emergence of a new technology, coined as Ambient Intelligence (AmI) [AmI, 2005]. In an AmI fueled intelligent environment the computer dissipates, becoming one with, while the environment becomes responsive to the user needs. Information is processed across millions of distributed microcomputational units (usually consisting of a microsensor and a micronic computational unit) which communicate with each other to anticipate and respond to user's intent or goal. Such an intelligent AmI environment for bridge monitoring is envisioned by us to be composed of the following components (Fig. 1): e-Monitors, e-Alarms, e-Communicators and an intelligent decision system. Each of these 'e-Components' are e-Gadgets (eGt, 2005). Extrovert Gadgets (e-Gadgets) is an EU research project (Extrovert-Gadgets, 2005) in relation to the "Disappearing Computers" project, which *focuses on creating a generic Gadget-ware Architectural Style (GAS), deciding the degree and locus of "intelligence".* The e-Monitors are small size smart sensor nodes which are to be inserted in the concrete before the bridge deck concrete is poured. Each e-Monitor is composed of a set of sensors (Table 1): vibration sensor, delamination sensor, corrosion sensor, stress/strain sensors, humidity sensor, and crack sensor. The e-Monitors continuously sense the "required data" and report it to the e-Decision Maker with the help of e-Communicators, which would decide the required action to be taken on the basis of the defects if present in the bridge. In case of emergency, the e-Monitors make decisions with the help of emergency response agents without sending data to the e-Decision Maker, and actuate e-Alarms for further action to be taken, as it will be detailed in Section 3.

## 2. RELATED WORK

Pontis (Pontis, 1990) is a stand alone bridge management system developed by US Federal Highway Administration which assists bridge engineers in rehabilitation and maintenance processes of bridges. They are helpful in keeping the record of the bridge in the database and present different kind of results in the form of graphs. The difference from our e-Gadget approach to bridge monitoring is that ours is intended to be fully automated with data being provided to the "management system" with the help of e-monitors and e-communicators. BRIDGEIT (BridgeIt1993), also a bridge management system, unlike our e-Gadget approach, requires data to be fed in to produce results similar to Pontis. In (Edward, 2004) a framework of intelligent wireless sensor networks is presented for structural health monitoring. The authors of the paper emphasize on low level hardware and communication issues and the monitoring methodology including damage detection based on localized changes and vibrations. The brief analysis of energy consumption is also presented in the paper. Different research communities have carried out research on individual bridge problems (Brent 2005, Kuang 2003, Liu 2003, Christopher, and Hoon 2004).

There has been a lot of work (Davy 2004, MAA, Ulieru 2002, Ulieru 2005, Tognalli 2005, Ulieru 2006 ) on context aware systems, agent architectures, and holarchic structures but according to the authors' best knowledge, e-Gadget based approach with emphasis on context and agent based design for remote bridge monitoring has not been taken up by any one till now.

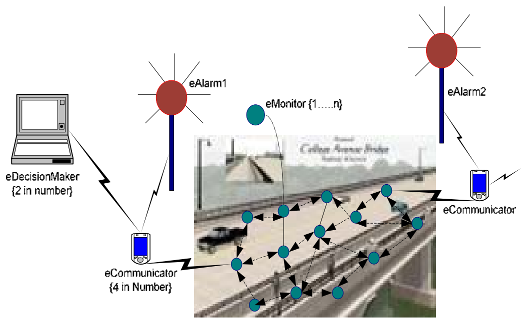


Figure. 1 System Architecture

## 3. DESCRIPTION

### 3.1 Problems that lead Bridge to Failure

The main problems that cause the bridge to fail comprise of *cracking, delamination and corrosion* (Cem, 2006). Cracking is a common problem associated with bridge decks. Cracks vary in size from hair size to wider deep cracks. A delaminated bridge deck is that which, when struck with a hammer or a steel rod, gives off a hollow sound, indicating the existence of a nearby laminated-fracture near the surface. The phenomenon of laminar separation in the concrete bridge deck is called delamination (Persson, 2000). Corrosion is the rusting of the steel bars in the presence of water and air and certain chemical compounds. These are the basic problems which, when not addressed, ultimately lead to big problems and result in disasters. The Collapse of the Silver Bridge (Chris, 2001) is an unfortunate crystal clear example in this regard. Natural phenomena's like earth quakes and strong winds can also cause damage to bridges and create emergency situations.

### 3.2 Contextual Information taken by sensors

From each of the sensor value some contextual information can be extracted as shown in the table 1. The over all context of the current situation of the bridge can be extracted by combing the contextual information from

Table. 1. Contextual Information

| Sensor Group | Signal | Location of Sensor | Signal Level | Contextual information |
|---|---|---|---|---|
| Humidity | Humidity level | In concrete deck | Humidity is high | Water is present in concrete |
| Crack | Crack dimension | In concrete deck | Dimension value is high | Crack is deep and wide |
| Corrosion | Corrosion Value | In concrete deck | Corrosion value is high | Water with salts is reaching the steel |
| Delamination | Delamination Intensity | In concrete deck | Intensity is high | Corrosion or cracks are making this |
| Accelerometer | Acceleration | In concrete deck | The value is above threshold | Earth Quake |
| Stress/strain | force | In concrete deck | The value is above threshold | Some Bridge Structure is about to fail. |

individual sensors. For example the context "emergency" can be drawn from the contextual information deduced from the individual sensors as shown in table 2.

Table 2. Drawing Context from contextual information

| Situation | Sensor Data |
|---|---|
| Emergency | If the stress/strain value is beyond threshold and the acceleration is very high, and the cracks size has increase than its emergency. |
| Repair required | If the humidity value is high, acceleration is normal, stress/strain values are normal, corrosion is 15 %, and there are hair line cracks, then non protective repair is required |

### 3.3 e-Decision Maker

A "decision tree" based e-Decision maker can be employed to get the required actions that are required to keep the bridge in running condition. The decision tree for e-Decision maker is partially shown in Fig.2. The e-Decision Maker in other words is a rule based expert systems to assist the bridge engineers in adopting the maintenance strategy. A rule for the e-Decision Maker can be:

*IF*, the age of the bridge is OLD AGE
*AND* the level of humidity is HIGH, *AND* corrosion value is GREATER THAN threshold value, *AND* stress/strain Values are LESS THAN lower bound *THEN* grouting is required.

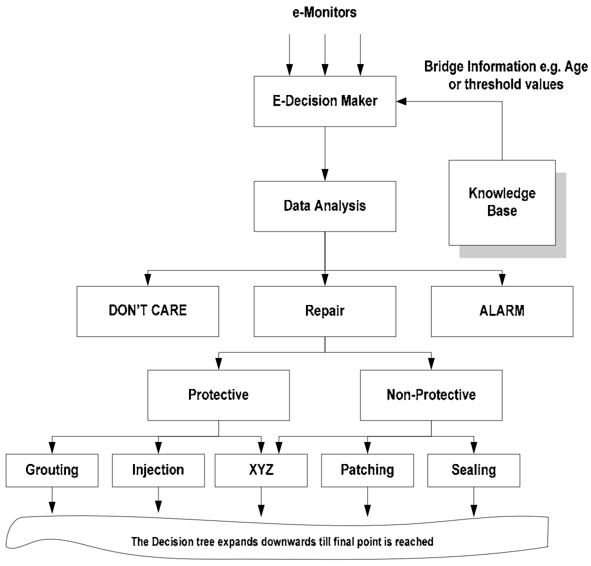


Figure 2. Decision Tree for e-Decision Maker

All the rules can be fed in the knowledge base, with other information related to the bridge, like bridge age, bridge ID bridge location, which can be used by the inference engine of the expert system to infer the required strategy for the maintenance of the bridge.

## 4. CONTEXT ONTOLGOY

The extensible context ontology [11] developed for our bridge monitoring application is shown in Fig.3. The four main components of this context ontology are: user, services, environment, and platform. The user interacts with the system via the user interface of the resource platform. The platform consists of two parts: a resourceful and a resource constrained platform. The resourceful platform mainly supports the expert system to infer the current bridge conditions and suggests actions to maintain the bridge. The resource constrained platform consists of hardware (radio interface, MSP430 processor, memory and radio) and software (lightweight operating system, data processing algorithms and communication protocols). Services use the software provided by the platform to inform the user regarding the bridge status and to act in cases of emergencies (e.g. earth quake).

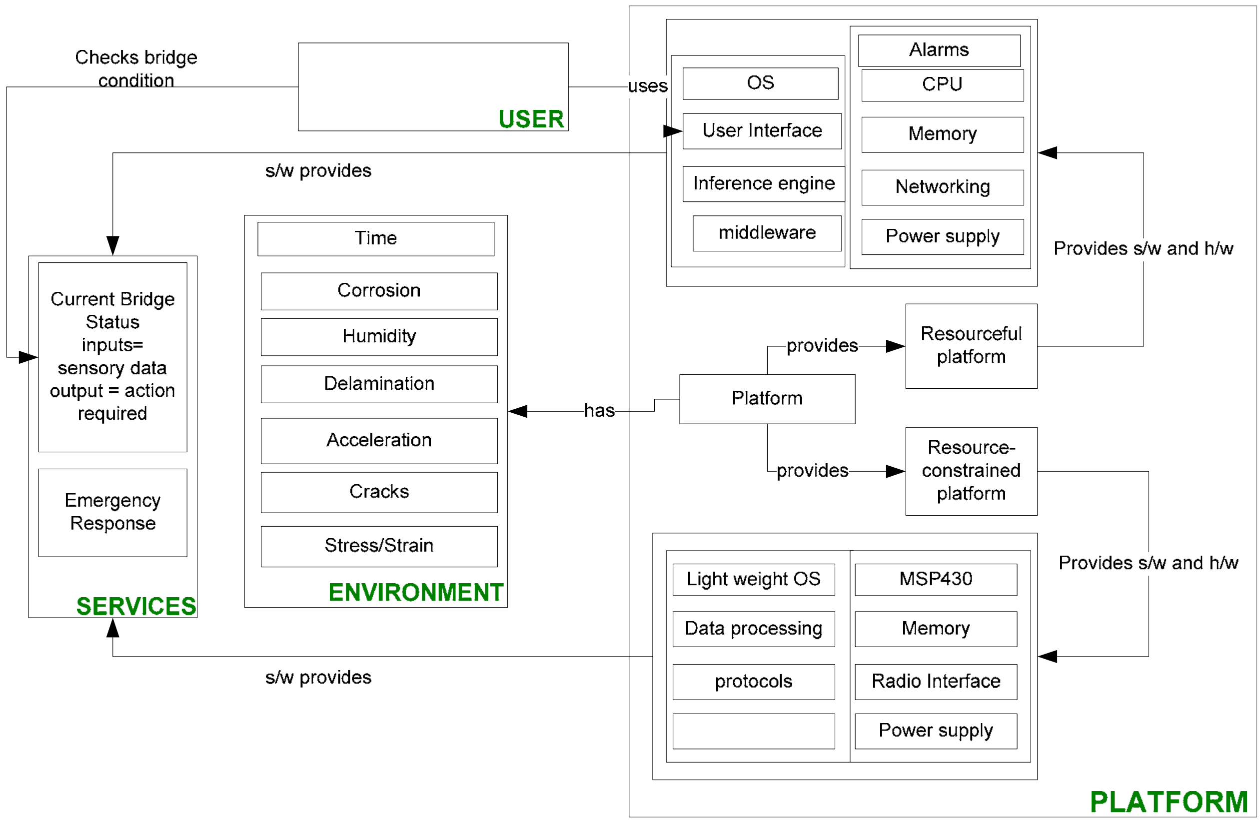


Figure 3. The Context Ontology

## 5. AGENT ARCHITECTURE

### 5.1 Topology and Communication Agent

The topology and communication agent resides in e-Monitors for self-organization and routing of information. (Figure 4.) As soon as the e-Monitors are deployed, e-communicator would initiate the "neighborhood registration" process by sending a broadcast message "register me". E-Monitors in one hop neighbors would get the message, store the information regarding the e-Communicator, and forward it by marking in the message the cost to reach the e-Communicator field, and its own locally unique address. The topology and comm. agent would register themselves with the neighbor e-Monitors by re-broadcasting the "register me" message. Each e-Monitor would send its cost and address in a "register me" message. In this way, each e-Monitor would know about all its neighbors and cost towards the e-communicator. A stigmergic optimization strategy inspired from how ant colonies function is used to un-register those eMonitors

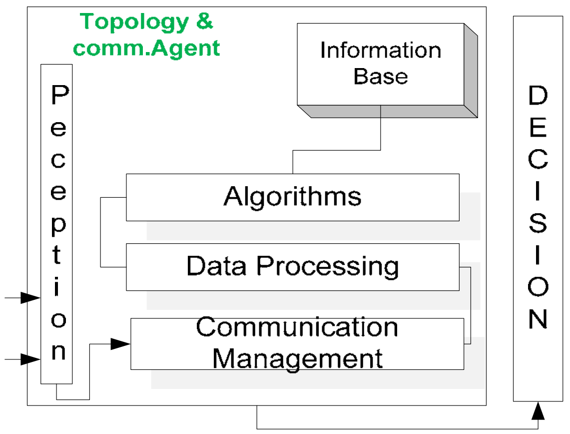


Figure 4. Topology and Communication Agent

who do not have enough energy to pass on the messages of their neighbors towards the destination. (In ant colonies (Yahya 2001), when there is a shortage of food, the ants with food stored in their stomach turn into feeder ants and feed the ants with no food. In a similar way, e-Monitors with energy below lower bounds can notify others not to "eat their energy by using them as intermediate nodes" but rather use another nodes.)
An e-Monitor with almost depleted energy would send "un Register me" message to its neighbors. In this way the un-registered e-Monitor would not be used while sending the information to the e-communicator. (Would be excluded during routing decisions). The cost field can be a function of the number of hops toward the e-Communicator and remaining energy of the e-Monitor. All the information is stored in the information base, which is used for routing and topology maintenance purpose. The topology and Communication agent is also responsible for implementation of this medium access scheme. All the data received from the sensors, is processed, formatted, and sent to the decision layer of the expert system with the help of routing algorithms. The above mentioned scheme can prove to be very scalable.
The e-Monitors can be inserted at any time. It would not affect any of the e-Monitors other than the neighbors which would simply register the newcomer. Similarly, the "death" of an e-Monitor would not affect other e-Monitors because it would only be unregistered after some amount of time.

### 5.2 Emergency Response Agent

The emergency response agent (ERA), Figure. 5 would also get the data from the sensors available in an e-Monitor. Before sending the data to the e-Decision Maker, the ERA would analyse the data, by comparing it with the threshold values available in the information base. If the data from sensors is above the threshold values, the ERA would immediately, actuate an e-Alarm for necessary action (blocking the bridge for further usage and informing city services). A set of pre-designed rules based on the sensory data can be provided in the information base for decision making. In case of emergency, the ERA would notify the topology and communication agent, so that the later can transfer the data keeping in view only "minimize delay aspect" and keeping aside the energy aware requirements.

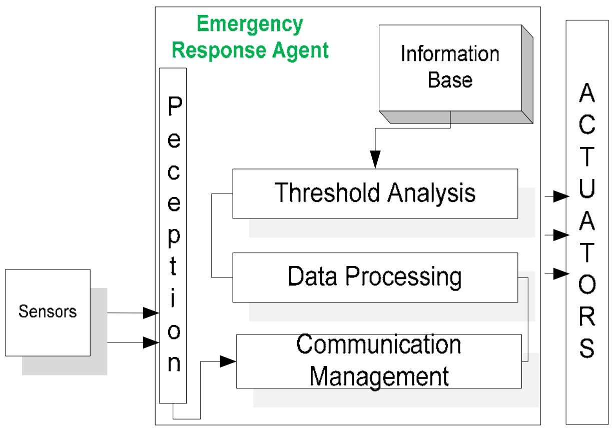


Figure 5. Emergency Response Agent

Deliberative agent architecture is selected for the development of agents, as opposed to a reactive one. Actions are always computed after analysing sensor data with the help of pre designed rules and reasoning.

## 6. GOAL BASED INTERACTION

The e-Gadget world is based on goal-based interaction

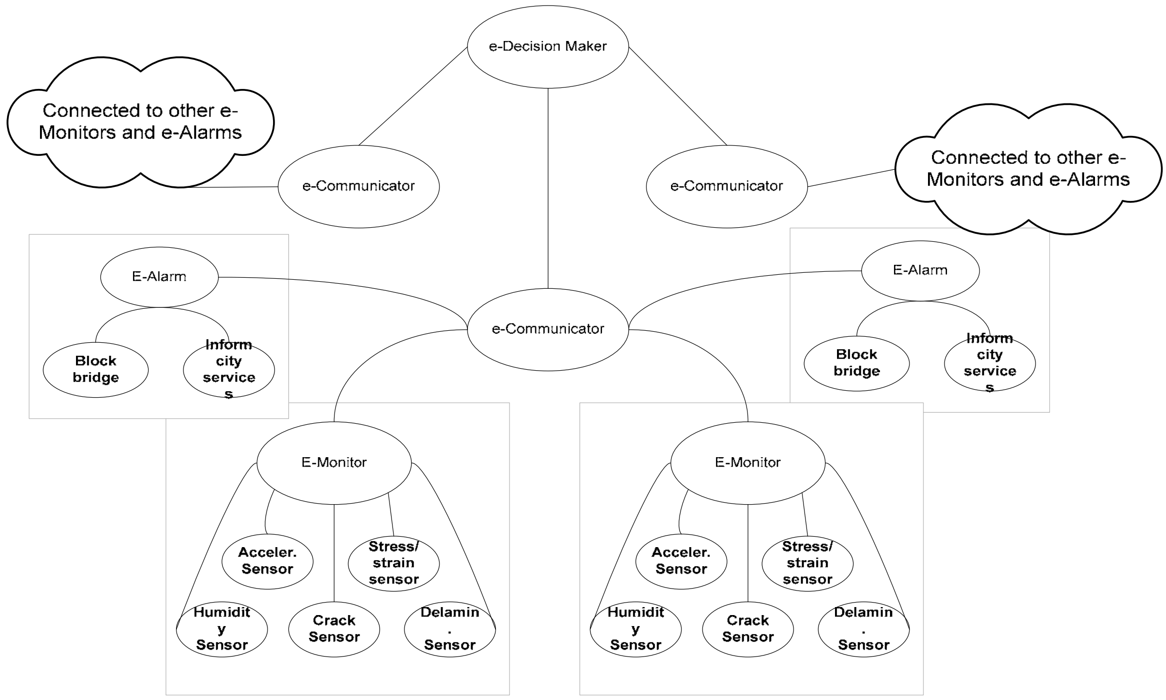


Figure. 6 Holarchy of e-Gadgets

between the different components. Public safety and in time maintenance are the user's goals. These goals are reflected by doing intention analysis. Intention Analysis, in this case is automated bridge monitoring. To achieve user's goals based on intention analysis, strategy planning is required. Strategy planning in this case is to monitor the bridge condition continuously.

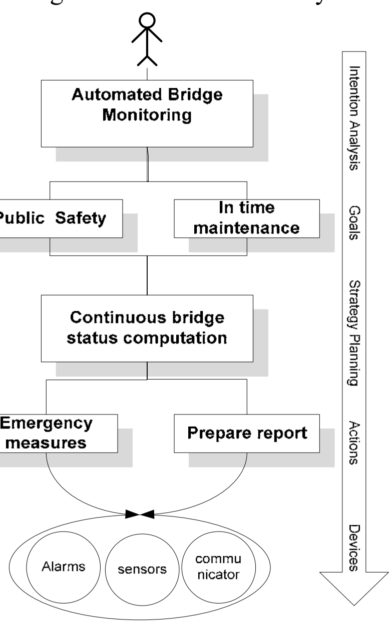


Figure 7. Goal Based Interaction

Finally certain actions are required to achieve the user's goals. The actions in this case are: preparing a detailed

report by the e-Decision maker for the user to adopt some strategy for bridge maintenance or are emergency measures initiated by the emergency response agent in case of emergencies. The goal based interaction between different components is shown in Figure 7.

## 7. E-BRIDGE MONITORING HOLARCHY

Inspired from (Maja 2006), the holarchic structure of e-Gadgets is shown in Figure 6. The holarchic structure is composed of four sub-holarchies, each having its mediator (a single entry and exit point), and the data collected at the lowest level of holarchy is always sent to the highest level of the holarchy with the help of a mediator of each of the sub-holarchies. The holarchy presented here can be very useful for the collection of data to produce results which can assist bridge engineers in the maintenance and rehabilitation process or to act in case of emergencies. After the deployment of the e-Bridge (a bridge with our e-Gadget world), the e-Decision Maker would ask the e-communicators to register themselves with it. All the e-communicators within the range of an e-Bridge would register themselves with the e-Decision Maker, which can be done via a "mediator" at the highest level of the holarchy. The e-Communicator would then register all the e-alarms of the e-bridge in a similar fashion. As a sub-holarchy of the system, eAlarm will register with it at the lowest level nodes with in that sub-holarchy. The e-Communicator would than send a simple broadcast message to the e-Monitors which would start the construction of topology for communication discussed in section 5. The e-Monitor sub-holarchy is composed of the leave nodes (sensors), which gather the required data and send it to the highest level of the holarchy for analysis purposes.

## 8. CONCLUSION AND FUTURE WORK

The proposed e-Bridge monitoring system is a useful way to monitor bridges. It would add to public safety, reduce bridge maintenance cost, avoid human errors while surveying bridges, and respond well in emergency situations. The main limitation is providing energy supply to the e-Monitors. To overcome this difficulty we aim to exploit the vibration available in the bridge to scavenge energy, which would prolong the life (energy availability) of the e-Monitors with about fifty years (as much as usually a bride lasts.). To achieve this energy aware routing and MAC schemes would enhance the energy consumption in e-Monitors for this particular application.

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