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Conceptual Design of Multi-agent System for Suramadu Bridge Structural Health Monitoring System

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Abstract

Wireless Sensor Network (WSN) is small embedded devices deployed in large scale network with capability to sense, compute, and communicate. It combines modern sensor, microelectronic, computation, communication, and distributed processing technology. WSN has been taking an important contribution in structural health monitoring system, especially in Suramadu Bridge, one of the longest span bridges in Indonesia connecting Surabaya (East Java) and Madura Island. Due to subjected by environmental circumstance, it is necessary to implement intelligent and autonomous WSN to monitor the bridge condition, detect the bridge damage, and send warning message to bridge users when unsafe condition occurs. The multi-agent system is a promising approach to be implemented on intelligent and autonomous WSN, especially in the bridge structural health monitoring system. In this approach agents are empowered to have several intelligent learning capabilities for structural monitoring, damage detection, and prediction. This paper describes multi-agent system conceptual design that will be implemented as model of long span bridge structural health monitoring system considering system architecture and agent organization.

Keywords: wireless sensor network, structural health monitoring system, multi-agent system

1. Introduction

Today, sensor technology development grows rapidly with capability not only for sensing and signal acquisition, but also for computing and communicating to other devices. This sensor technology is called Wireless Sensor Network (WSN). It also uses internet technology as communication media. WSN gives significant effects and chances for further research in several application developments especially in bridge structural health monitoring systems.

In the case of WSN application for long suspension bridge structural health monitoring system, structural aging and environmental condition are subjects that must be fully monitored. Thus, according to these considerations we need to monitor and detect deficiency or deformation structures due to normal operation or environmental effects such as ambient temperature and humidity. In addition, entire structural monitoring is necessary to be conducted after extreme condition like disaster. In order to quantify the measurement of structural performance, it is necessary to monitor and evaluate integrity of civil constructions. Thus, Structural health monitoring became a trending method and research topic [1].

Suramadu is the longest span suspension bridge, with a lot of cables, in Indonesia connecting Surabaya City and Madura Island. As an interisland bridge (Java and Madura Island), Suramadu is subjected to operational and environmental influence that will affect to its performance. Therefore, it needs a structural health monitoring system that is responsible for information dissemination of environmental variables affecting directly to bridge structure and identify the cause of bridge deformation.

Currently, Suramadu Bridge has been deployed by a lot of sensors performing specific roles and tasks. However, it still uses client-server approach in which each sensor transmits its sensory data one hop from one sensor to concentrator or sink, also called as data acquisition unit (DAU). This approach also follows one sensor node as perceptor achitecture described by [2] in which all sensor nodes act as perceptor and they are coordinated by one centralized concentrator. However, The drawback of this architecture is in scalability in which the system will be down if center node fails to work and unbalance energy consumption if we implement

multi hop data transmission where sensor nodes that is closest to the concentrator will transmit more data than the others [3]. In other hand, one of issues that must be addressed when implementing WSN is autonomous operations that has not been implemented in Suramadu Bridge WSN yet. In this case, autonomous means that sensor nodes should organize their own network cooperatively using distributed algorithms and not only send packets or execute application programs, but it is actively involved in determining decision how network is operated, called in-network data processing [4].

WSN in Suramadu Bridge has not utilized the sensor node capability in computing yet where data processing performed in centralized manner is shifted to decentralize manner. It allows a piece of detection and prediction process to be performed in each sensor node. Therefore, we need to consider distributed architecture of WSN that combines centralized and distributed processing.

In this paper we propose agent-based approach for in-network data processing that will be implemented as a model for bridge structural health monitoring systems, especially in Suramadu Bridge. According to [5], Agent is computer system with capability to perform autonomous action in its environment in order to achieve its goals. This definition of agent is convenient for WSN that requires autonomous operations. To design WSN based on multi-agent system, at least four issues that should be considered: system architecture, mobile agent itinerary planning, middleware design, and hardware design [3]. In this paper we describe architectural design and agent organization.

In the agent architectural design, we propose concept of WSN architecture in which network is segmented into clusters coordinated by cluster head, also called DAU (as mentioned above). In this network, we modified mobile agent-based WSN (MAWSN) described in [6], hybrid architecture described in [2], and agent organization described in [7]. In the context of agent organization, we consider agents performing spesific tasks are deployed on each sensor node and coordinated by a manager agent. We also implement the intelligent mobile agent for data aggregation.

When implementing the intelligent mobile agent, we consider the concept of itinirerary planning as passive learning in order to make sure that mobile agent will visit all sensor nodes in efficient manner. We use the approach of mobile agent multiple itinerary planning to solve delay or scalability problem [3]. Combination of genetic algorithm and reinforcement learning probably will give better result in mobile agent implementation and they are our main research focus. Genetic algorithm has been proved to solve combinatory problems, whereas reinforcement learning, which is sufficient to be implemented on a sensor node [8], empowers agent to make their own decision. We will also leverage Markov Decission Process (MDP), as a part of reinforcement learning model, and Belief-Desire-Intention (BDI) as two approaches that can be mapped each other [9] to create the intelligent agent deployed on a sensor node.

In the context of bridge structural health monitoring system, we propose two main actor roles. First, agents deployed on each sensor performing spesific task, e.g. sensing environmental variable, outlier detection, resource monitoring, sensor node organizing, and mobile agent transmission. Second, operators in monitoring and controlling center will follow up data that have been gathered for further processing and determine operational policies according to the bridge environmental condition.

This paper describes conceptual design of multi-agent system for Suramadu Bridge Structural Health Monitoring System. It is divided into five sections. Section 1 is introduction, Section 2 describes WSN in Suramadu Bridge, Section 3 describes agent organization and roles, Section 4 describes agent framework consideration, and Section 5 describes conclusions.

2. Wireless Sensor Network in Suramadu Bridge

Structural health monitoring system (SHMS) is a system performing sensing utilization and in-site and non-destructive analysis about structural characteristics, including structural responses, to identify damage detection, determine damage location, predict severity level of damage, and evaluate the effects of structural damage. SHMS gives great challenges for damage detection and structural condition prediction.

There are several functional requirements that must be considered when designing structural health monitoring system on Suramadu Bridge. First, system must implement advanced techniques, good performance, long term stability, and economic value rationality.

Second, system has capability to transmit data, process view, archive document, and share long distance information. Third, system is able to collect data synchronously, real-time, long term, and hierarchically. Fourth, system has capability to assess, control, and calibrates itself. Fifth, system is able to identify damages and evaluate structural health. Finally, system is reusable and upgradable.

In context of application process, structural health monitoring system in Suramadu Bridge has ability to report environmental condition including changes in work and load of the bridge, report strain and deformation status of bridge main components, record abnormal or anomaly loading condition (e.g. storm, earthquake, and overloaded vehicle), identify main components damage of the bridge and failure accumulation, send warning message when detecting abnormal condition, disseminate information for load lifting calculation, and management purpose especially maintenance management. Therefore, structural health monitoring system in Suramadu Bridge must consist of sensor systems, data acquisition and transmission systems, data processing and control systems, and structural health evaluation systems. These subsystems must provide capability to run operation autonomously both in normal and abnormal condition. They must able to communicate each other and keep system integrity when a failure occurs. These subsystems will be implemented using multi-agent systems described in Section 4 of this paper.

In operational function perspective, structural health monitoring system in Suramadu Bridge is divided into three levels of hierarchy. First is data collector level. In this level sensor system collects input signals of sensor, data pre-processing, and data transmission. Second level is data processing and analysis that is responsible for processing, archiving, viewing, storing, and collecting all data gathered from sensor nodes. The last level is structural health evaluations in which data analysis and document management are performed.

Figure 1. Sensor deployment on the middle span of Suramadu Bridge

Suramadu bridge structural health monitoring involves application deployed on sensor devices (see Figure 1). Quantity of sensor node deployed on the bride must coverage entire bridge. In Suramadu Bridge, there are 397 sensor nodes performing various roles (See Table 1). As consequences, this system requires accurate and proper deployment.

Table 1. Label Description of Sensor Deployed on The Middle Span of Suramadu Bridge

Sensor Type	Label	Qty
Bi-Axial Anemometer	B-ANE	2
Tri-Axial Anemometer	T-ANE	10
Structure Steel Temperature Sensor	SST	24
Structure Concrete Temperature Sensor	SCT	47
Road Temperature Sensor	RT	4
AF Temperature and Relative Humidity Sensor	AT&RH	8
Corrosion Sensor	CS	8
Global Positioning System	GPS	18
Force Ring	FR	72
Steel Strain Gauge	SSG	62
Concrete Strain Gauge	CSG	64
Strain Rosettes Gauge	SRG	4
Single-Axis Accelerometer	S-ACC	11
Bi-Axial Accelerometer	B-ACC	14
Tri-Axial Accelerometer	T-ACC	1
Seismic Accelerometer	SE-ACC	2
Bi-Axial Tilt meter	B-TILT	14
Digital Video Camera	DVC	22
Displacement Transducer	DT	8
Weight-In Motion System	WIM	2
Total Sensor		397

2.1. Data Acquisition and Transmission System (DATS)

DATS is responsible for data collecting, signal conditioning, data storage, and data transmission. When designing DATS, it is neessary to understand about sensor type, sensor quantity, sensor localization, and monitoring method. To reduce and prevent distortion of signal and electromagnetic interference, all data acquisition unit, including sensors, must be deployed in efficient manner and secure area. For efficiency, fewer data acquisition units are better. DATS with proper installed software and parameter configuration for data acquisition must able to collect, pre-process, and store temporary data.

Functional design of DATS at least should follow four requirements. First, each DATS station, called Data Acquisition Unit (DAU), will be placed on somewhere corresponding to sensor placement (see Figure 2). Second, all DATS are configured properly to ensure that system development, integration, execution, maintenance, and improvement will be conducted easily. Third, System is able to run its services for long duration, 24 hours a day, even when routine maintenance is performed or abnormal conditions occurs. The last requirement is dynamic topology. It means that when one of system part is malfunction, the system reconfigure their network autonomously.

2.2. Data Processing and Control System (DPCS)

DPCS in Suramadu Bridge consists of servers with capability to extract, post-process, archive, and store large amount data. It is also responsible to view data to user. In this system, all data are processed into information, and then information is transformed into knowledge.

There are at least two DPCS functional requirements that should be implemented. First, DPCS manages communication among all DAU in WSN. In other hands, DPCS also receives a real-time collection of collective data from all DAU. Second, digital data that has been pre-processed in DAU are sent to DPCS using internet protocol through wireless network. Then these data will be stored in DPCS for short or long time duration.

Many of raw data and processed data will be store automatically at determined interval in storage devices. The available pictures then will be sent to DPCS user interface to be viewed and controlled. From two DPCS units, operators or users can request views about all current values, service status, reports, or notes about events, change specific parameters, add/delete/edit data view at routine monitoring, change description of status, alarm, and engineering unit, add new status of data view to system, retrieve list of database and program, perform data analysis, and request historical reports.
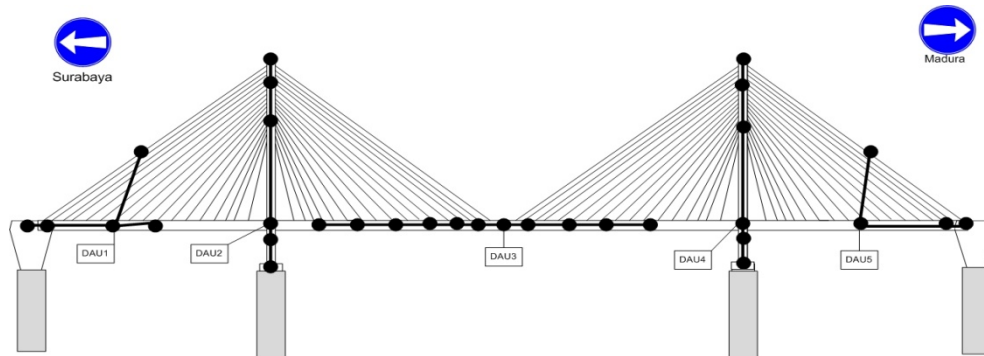
Figure 2. Data Acquisition Unit (DAU) placements on Suramadu Bridge

2.3. Structural Health Evaluation System (SHES)

The core of structural health monitoring system is structural health evaluation system (SHES). In the monitoring room, system evaluates load capacity and dynamic works of structure and identifies the potency of structural damage using online and real-time data that have been processed by DPCS. Thus, it is necessary to implement two types of computer. First computer, called SHES server, performs problem solving for analytical work of limited elements such as static non-linear analysis, dynamic analysis (wind, seismic, and vibration), interaction between fluid and structure, and structural health evaluation. Second computer, called SHES-WK (SHES Workstation), takes into account in data graphical analysis and reporting.

In the context of structural health monitoring, Suramadu Bridge WSN takes into account in monitoring of highway loading effects, monitoring of temperature effects, monitoring of wind effects, monitoring of seismic effects, and monitoring of corrosion. In the context of structural damage detection, WSN can be utilized for vibration-based damage detection in which we can use methods such as frequency changes, mode shape changes, modal damping changes, frequency response function changes, mode Shape Curvature Changes, modal Strain energy changes, and flexibility changes for vibration-based damage detection.

3. Agent Organization and Roles

In our research, we will use a methodology based on agent-oriented software engineering (AOSE) and propose implementation of intelligent agent characteristics described in [5]. AOSE leverages development cycle starting from analysis to coding by using model-driven engineering (MDE) approach [10]. There are two main activities that should be performed in this methodology: identifying platform independence module (PIM) and platform specific module (PSM). In PIM we describe agents, their roles, information they exchange, and their interaction. In PSM we describe devices platform both hardware and software platform that will support multi-agent system in WSN.

3.1. Agent Organization

There are four types of WSN architecture implementing multi-agent system organization: one sensor node as perceptor, one agent each sensor node, mobile agent, and hybrid architecture [2]. In the case of Suramadu Bridge SHM, we will implement hybrid architecture in which it combines many agents each sensor node and mobile agent (see Figure 3). This architecture is a model of agent organization proposed in [7] with additional our modification. It introduces agents on middleware layer of sensor node and separates agents into two layer of middleware: middle and application layer.

In middle layer, there are two agents, resource agent (RA) and sensing agent (SA). RA is an agent with capability to make decision related to memory and power usage control. This agent determines cost that should be prepared by other agents to perform its tasks. This agent also makes decision based on Belief-Desire-Intention model (BDI model) whether to accept or not executing another agent request according to cost consideration. SA is an agent that has interest in physical variables and has access to sensor components (e.g. temperature sensor,

accelerometer, light sensor, etc). This agent has responsibility to make decision based on BDI model for outlier detection and dissemination of physical variables.

In application layer, there are two types of agent: manager agent (MgrA) and mobile agent (MA). MgrA is an agent that is responsible in managing, organizing, and negotiating with other agents under its coordination. MgrA also implements BDI model and Markov Decision Process (MDP) model to make decision. MA is an independent mobile agent and also implements BDI and MDP model, it performs communication with MgrA to make cooperation. It is a special agent that performs migration from one sensor node to another for data collection.
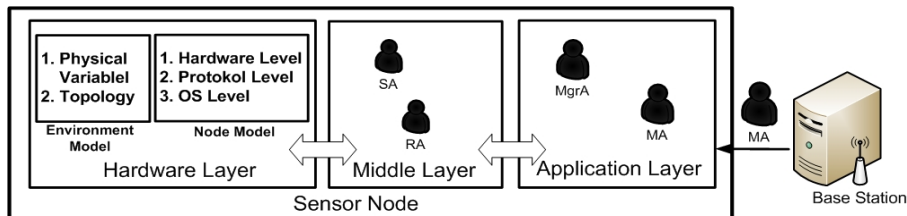
Figure 3. Proposed multi-agent hybrid architecture in WSN

In the context of mobile agent (MA), we implement sink node as a MA dispatcher. It may be a sensor node with powerful capability or other computer systems. In this approach sink node sends a MA to target area to visit each sensor node in that area. Data in sensor node is eliminated and collected by the MA. Then, MA with its collected data returns to sink for further data processing. This approach will reduce communication tasks among sensor nodes.

We implement multi-agent system in WSN and modify agent organization proposed in [12]. Here, we define six definitions:

1) DPCS agent is the main agent of SHMS. It is placed in DPCS and dispatches several MAs to aggregate data from DAU sink nodes and coordinates sensory data fusion. DPCS agent is also the coordinator of DAU agent.

2) DAU agent, placed in DAU (also called as sink), dispatches multiple MAs to collect data from worker sensor nodes in their cluster. DAU can be called as cluster head that coordinates worker sensor under its cluster area. There are two clusters coordinated by DAU: Girder DAU (GDAU) and Environment DAU (EDAU).

3) Worker sensor nodes are responsible for data collecting, signal conditioning, data storage, and data transmission. MgrA, RA, and SA are installed on each worker sensor node (see Figure 3). It receives and transmits various mobile agents dispatched by DAU agent. A worker sensor node periodically performs sensing process around their environment and stores sensing data in local memory.

4) Director Agent (DA), deployed on DPCS, is an entity where agents and its capabilities are registered. The main role of DA is storing information about MA and agent group profiles with its capabilities in its local database. When a requester requests a preference, DA performs matching process to find related sensor node capability and sends response back a set of appropriate events to requester.

5) Requester may be a human or other agents who requests information to system.

6) Weight in Motion (WIM) sink is a cluster head that coordinates worker sensor nodes measuring the axle weight of passing vehicle, velocity of the vehicles, and distance between axles. Here, the traffic load of the bridge can be measured. It also dispatches a mobile agent to collect data from its members and evaluate not only traffic load of the bridge, but also identify the cause of damage.

The architectural design described above modifies conceptual architecture explained in [3] that describes two types of architecture: architecture in hierarchical sensor network and architecture in flat sensor network. It also implements in-hierarchical sensor network architecture described in [13] and combines two types architecture in flat sensor network: mobile agent-based distributed sensor network (MADSN), described in [14], and mobile agent-based WSN (MAWSN), described in [14]. In the middle span of Suramadu Bridge, there are five DAUs deployed on the bridge (See Figure 2), called DAU1, DAU2, DAU3, DAU4, and DAU5

respectively. DAU may be a single-board computer (SBC), e.g. Raspberry, with additional base station, a device connecting DAU to sensor nodes.

As mentioned in our six definitions, each DAU coordinates two clusters: EDAU and GDAU. Each cluster consists of worker sensor nodes performing environmental sensing. A worker sensor in each cluster periodically performs sensing process around their environment and collects sensing data in its local database. When detecting an event, worker sensors send an exploratory message to DAU. Then, DAU agent dispatches multiple MAs to collect data and accumulate its size hop by hop. After MA returns to DAU, DAU agent sends notification message to DA, to indicate that there are data that ready to be further processing. DA then dispatches MA to process data collected in DAU. When a requester requests a preference, DA performs matching process to find related DAU capability, sends MA to DAU for data gathering, and sends response back a set of appropriate events to requester. Figure 4 shows an example of sensor network topology coordinated by DAU1.

One of the organization goals that must be achieved is energy efficiency to make a long life WSN. Strategy-based communication [15] will be considered in this research. It defines three aspects that should be considered: information importance communication, which decreases total communication among sensor nodes, preventing unnecessary inter-sensor information exchange, and data concatenation. The first and second aspect will be solved by implementing distributed reinforcement learning [16], described later in this section, whereas the last aspect will be solved by implementing mobile agents that performs synthesis solution, called solution fusion among mobile agents.
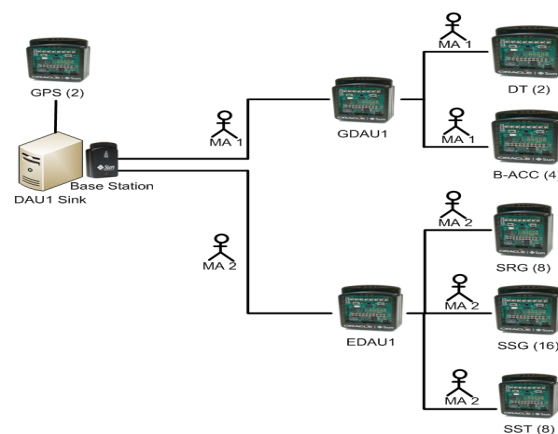

Figure 4. An example of sensor network topology coordinated by DAU1

3.2. Mobile Agent Migration

One of important issues that should be considered in designing multi-agent system in WSN is MA migration planning, also called itinerary planning. Itinerary is a route that should be followed by the MA when performing migration [13]. There are two main issues that must be solved by the system autonomously related to itinerary planning: selecting a set of sensor nodes that will be visited by the MA and determining a sequence of sensor nodes that will be selected by the MA considering energy efficiency [3]. We will implement three types of itinerary planning: static planning [14], dynamic planning [13], and hybrid planning [17].

In static planning, MA migration route is absolutely determined by sink node before MA is dispatched. In our case, sink node is DAU. DAU uses current global network information and obtains efficient route before sending MA. Powerful technique that can be considered in static itinerary planning is Genetic algorithm (GA). Using this algorithm, MA only visits a sensor node once a round [18]. In this research we use GA considering two optimization objectives: the distance between two sensor nodes (determined by received signal strength indication) and remaining energy in the next hop sensor node. In dynamic planning, each MA determines next sensor node that will be visited from current visited node. Dynamic agent route also must consider trade-off between sensor node distance and remaining energy. Dynamic planning

approach will search a sensor node with enough remaining energy for dispatching the MA [13]. Finally, in hybrid planning, selecting a set of visited node is static whereas determining a sequence of visited node is dynamic.

In the context of Data fusion pattern, there are three types of pattern that should be determined in the architecture: conventional pattern, single MA-based pattern, and multiple MA-based patterns. In conventional pattern, data collected by sensor node is transmitted from sensor to sink. This concept is the same as client-server paradigm. In single mobile agent, only one mobile agent is dispatched to all sensor nodes, whereas in multiple mobile agents, various mobile agents are dispatched from sink to sensor nodes. We will use multiple mobile agents.

3.3. Outlier Detection Agent

Agent capability that should be defined in WSN is outlier detection. When monitoring environment, agents that are implemented on sensor node have to identify and classify events. Therefore, it is necessary to ensure reliability and information quality in WSN. To avoid transmitting inaccurate data, real time data analysis should be conducted in each sensor node.

Due to uncertainty environment, a sensor node may be malfunction or produce inaccurate data. In addition, resource limitation such as limited processing, storage, bandwidth, and agent autonomy may cause inaccurate raw data. This is called an outlier [21], which a sensor node reads data that deviates from common data. An outlier may be caused by noise, data error due to hardware malfunction, or malicious attack. To determine a proper method that can be implemented in a sensor node with limited resource, a technique of real-time outlier detection was introduced. This technique is performed locally by SA.

3.4. Agent Performing Reinforcement Learning

Another agent capability that should be considered when implementing multi-agent system in WSN is ability to communicate with its environment without tutor assistance [22], called Reinforcement Learning (RL). RL is on the top survey that the most appropriate technique for WSN optimization [8]. Therefore, RL is the technique that will be our main focus to be implemented in MA, MgrA, DA, and DPCS agent.

RL that will be used in our WSN is Distributed Independent RL (DIRL). The aim of DIRL is for agents' coordination in order to manage their own resource in distributed manner and eliminating communication among sensor nodes when coordination is performed [23]. In our research, each agent group deploy on sensor node is selfish and implement DIRL. It means each agent on sensor node modifies its behavior using RL algorithm to allocate tasks schedule autonomously by learning its utility corresponding to given state. The reward function for each task is described as combination between task output and remaining energy. In addition, it is necessary to ensure that global system behavior is the collective effect of individual agent. This responsibility belongs to MA and MgrA cooperation when migration process is performed. MA and MgrA are also responsible to update a reward.

3.5. BDI and MDP Agent

Belief Desire Intention (BDI) is reasoning process to determine actions that must be performed by an agent to achieve its goals. It involves two important processes: deliberation process that produces a set of the agent intentions or commitments and means-end reasoning that presents a sequence of actions correspond to selected commitment. Markov Decision Process (MDP) agent is defined as a state space (S_{MKV}), a set of actions (A_{MKV}), a reward function (R), and a state transition function (T_{MKV}), which defend on current state and performed actions. BDI agents implement descriptive approach in which they make a decision whereas MDP agents implement prescriptive approach in which they identify optimal decision. BDI agents are more tractable than MDP [9].

BDI model does not consider stochastic actions, BDI assumes that action taken by an agent always result desire effect, it is possible for intention plan to generate undesirable effects and causing the agent deviates from a sequence of states that has been planned before [9]. Therefore, reconsideration of intentions is required when the agent realize that current state is not under its plan. This phenomenon probably occurs when implementing mobile agent dynamic itinerary planning. Thus, we have to combine BDI and MDP agent so that we do not only develop agents to perform their task but also perform optimal performance. We place BDI and MDP behavior in MgrA and MA.

4. Agent Framework Consideration

The agent platform that matched with our desirable design is Agent Factory Micro Edition (AFME) [24]. It was design to adopt BDI paradigm in which agents follow sense-deliberate-act cycle [24]. It describes agent through Agent Factory Agent Programming Language (AFAPL) based on logical formal of belief and commitment. This language is used to encode agent behavior by determining rules defining condition when commitment is adopted. Unfortunately, AFME does not support strong migration. It means that AFME only support object state and data migration (weak migration), not code. There is a middleware platform that allows agent's code migration (strong migration). This platform is called Agent Platform for Sun SPOT (MASPOT). However, strong migration consumes more energy than weak migration [25]. Therefore, in this research, we focus on weak migration approach.

Agents that implements AFME consists of four components: perceptor, actuator, module, and service. Perceptor allows agent to sense and generate belief. Actuator allows agent to perform action to its environment according to generated belief. Module represents information space shared between perceptor and actuator. An agent may contain perceptor and actuator. These two components could not refer each other directly. Therefore, module is a space than can be used to share information between perceptor and actuator. Finally, service is information space shared among agents.

5. Conclusion

This paper describes multi-agent system in WSN in order to manage limited resource, especially energy and bandwidth, which can support data processing in distributed manner. Capability of current sensor node in computing allows us to implement in-network data processing on sensor nodes using agent oriented paradigm. When implementing multi-agent system in WSN in order to support in-network data processing, there are several aspects that should be consider: architecture consideration, middleware, mobile agent itinerary planning, and learning agent capability.

Implementing distributed WSN architecture in which network is segmented into clusters coordinated by cluster head is our proposed solution. In this network, we can implement agent organization in which each sensor node is deployed by agents that perform a specific task. These agents are coordinated by a manager agent. In the context of mobile agent, we have to consider itinerary planning that ensures the mobile agent visits all sensor nodes in each cluster in efficient manner. Genetic Algorithm is our main consideration. The last consideration is capability of agents to learn when they determine their own decision autonomously. There are many machine learning techniques that can be used to implement learning capability on an agent, but reinforcement learning is a technique that is sufficient to be implemented on a sensor node. Belief Desire Intention model and Markov Decision Process are approaches that can be considered when developing the intelligent agent deployed on a sensor node.

For future work, we are going to develop agent-oriented system that will be implemented on Suramadu Bridge. The next research agenda includes implementing mobile agent capability to determine efficient itinerary planning both using GA and RL in which BDI and MDP agents take into account.

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