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Integrating an Agent-based Wireless Sensor Network within an Existing Multi-Agent Condition Monitoring System

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***Abstract*—The use of wireless sensor networks for condition monitoring is gaining ground across all sectors of industry, and while their use for power engineering applications has yet been limited, they represent a viable platform for next-generation substation condition monitoring systems. For engineers to fully benefit from this new approach to condition monitoring, new sensor data must be incorporated into a single integrated system.**

This paper proposes the integration of an agent-based wireless sensor network with an existing agent-based condition monitoring system. It demonstrates that multi-agent systems can be extended down to the sensor level while considering the reduced energy availability of low-power embedded devices. A novel agent-based approach to data translation is presented, which is demonstrated through two case studies: a lab-based temperature and vibration monitoring system, and a proposal to integrate a wireless sensor network to an existing technology demonstrator deployed in a substation in the UK.

***Index Terms*—Condition Monitoring, Multi-agent Systems, Intelligent Systems, Sensor Networks.**

I. Introduction

Condition monitoring of high-voltage plant is recognized to benefit engineers by providing an assessment of current plant health, enabling optimized maintenance schedules to be made, and ensuring plant uptime. A recent CIGRE report [1] recommmends that the level of condition monitoring applied to power transformers should be proportional to the asset value, therefore for high-value, at-risk assets, monitoring schemes such as online dissolved gas analysis (DGA) may be used, but for lower value assets a suitable low-cost alternative should be used.

Wireless sensor networks are gaining in popularity for industrial sensing applications due to their relatively low cost and simplicity for retrofitting into existing infrastructure. They are particularly suited to power engineering applications as they do not require cabling, which will lead to shorter outages during installation and a lower capital outlay than their wired equivalent. This technology has previously been applied within the power engineering domain, in areas such as transmission system security [2] and substation temperature monitoring [3] [4], but to-date, such systems have been standalone. For wireless sensor network technology to make a valuable contribution to condition monitoring in the power domain, like any monitoring system, it must integrate with existing systems to allow monitoring engineers a unified view of equipment health.

This paper outlines steps required to integrate a wireless sensor network architecture, SubSense, with an existing agent-based condition monitoring system. An agent-based approach is taken to overcome each of these issues, including an implementation of a sensor network gateway agent that translates between bit-efficient and FIPA-based message formats, and a novel mechanism for data contextualization using a multi-agent approach, which uses a theorem prover to provide data on both electrical and sensor networks.

The authors propose the reuse of an existing sensor network ontology to leverage existing domain knowledge. Extensions to this ontology are proposed to allow it to be effectively integrated with the existing condition monitoring system.

Two case studies are presented to demonstrate different scenarios in which this system may be applied. The first is a laboratory-based experiment to periodically capture temperature and vibration data. The second case study outlines a proposal for a wireless sensor network to be added to an existing industrial demonstrator installed in a transmission substation in the UK. These case studies demonstrate that a multi-agent approach combined with wireless sensor networking can be used for a number of condition monitoring applications.

II. Multi-Agent Condition Monitoring Architecture

Across utilities, there is much variation in the approaches to condition monitoring of power assets. For oil-filled transformers, CIGRE Working Group A2.18 list 20 different groups of off-line test, and 10 types of on-line monitoring that can provide information about their health [5]. For GIS, Working Group 15.03 list 5 types of monitoring test for both on-line and off-line use [6]. Generally, utilities will implement a program of some subset of these tests, such as starting with periodic oil or gas samples, moving to on-line monitoring as defects are suspected.

The key issue is that there is no universal set of tests, sensors, or interpretation techniques that applies to all monitoring situations. As a result, a condition monitoring system ought to be flexible enough to accommodate and integrate multiple types of data and analysis, and extensible enough to allow the addition of new tests as required by the utility. Such a system should present all current health information about plant under study through the one interface, without requiring engineers to manually check multiple condition monitoring systems.

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To this end, a multi-agent condition monitoring architecture was created. Multi-agent system technology was chosen to underpin this architecture due to its capability for flexibility and extensibility [7]. The architecture itself comprizes three parts: high-level agent roles generic to condition monitoring tasks, patterns of communication between these roles, and an upper ontology of common message terms to facilitate communication.

There are five high-level roles that occur within the condition monitoring system, each performed by a separate agent. Data providers take data from an external source, such as databases, historical files, or web services, and parse it into terms from the agent ontology. The data provider can then respond to queries from other agents about the data they hold.

The second role is a service provider, which takes some data and performs some interpretation on it. Some examples are to take dissolved gas levels and perform fault classification using Duval's Triangle [8] analysis, or to take top oil temperature and calculate hot spot temperature. Service providers may also interpret the output of other service providers, such as an agent performing corroboration between hot spot temperature and DGA-suggested faults.

A third role is the data director, which matches up appropriate data providers with service providers. An archive agent role is required to store the output of analysis by service providers. Finally, an external interface role converts ontology-format data and information into an external format, such as writing report files or offering a web service interface. This is essentially the opposite task of the data provider, and can be used to populate an engineer's system interface with appropriate information.

Agents require a common language for communication. While there exist standards for message headers [9], the content of a message is application-specific and cannot be fully standardized. It has been proposed that the terms and concepts related to condition monitoring within the power domain are common enough that an upper ontology can be created, standardizing how to describe concepts such as transformers and measurements [7]. For this architecture, an ontology based on the Common Information Model (CIM) [10] was developed.

This architecture allows the deployment of a flexible, extensible, integrated condition monitoring system. New data sources can be added with the deployment of an appropriate data provider agent, while new techniques for data analysis can be deployed as additional service providers. Additional requirements on external access to information can be accommodated by deploying new external interface agents. In this paper, the external system is a wireless sensor network platform, discussed in the following section.

III. SUBSENSE WIRELESS SENSOR NETWORK PLATFORM

A multi-agent middleware platform was developed to allow condition monitoring agents to be developed and deployed onto a wireless sensor network. The platform was developed for SunSPOT sensor nodes, which comprize of a 180MHz ARM processor, 512KB RAM, 4MB flash memory, and optional multi-sensor board including a thermometer and 3-axis accelerometer for temperature and vibration sensing. These devices use the Java Mobile Edition (J2ME) programming language, which not only eases development of embedded applications but also simplifies integration with other Java applications such as the multi-agent toolkit described in the previous section. A J2ME version of JADE is also available, called JADE-LEAP [11], and although this system is tailored for devices such as PDAs and cell phones, it is not compatible with the SunSPOT architecture.

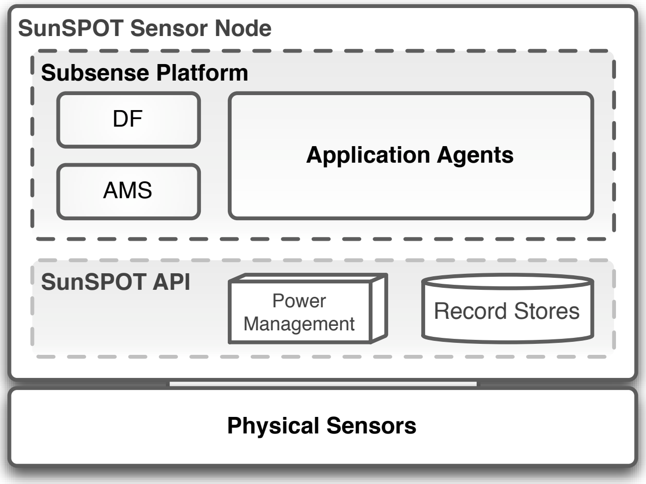

Fig. 1. Overview of the SubSense Architecture. The agent model is similar to the FIPA-defined model, although customised for an embedded environment.

A. System Architecture

The SubSense architecture is loosely based upon the JADE platform, with the aim of providing a familiar model with which to develop agents. An overview of the system architecture can be seen in Figure 1. The application programming interface (API) includes prototype classes for both agents and behaviors, specifically designed to take advantage of SunSPOT platform features.

Each sensor node runs an agent container which provides an execution environment for application agents, as well as containing a local Directory Facilitator (DF) and Agent Management Service (AMS) agent. The functionality of these agents is based upon a subset of the FIPA Agent Management Specification [9], amended for an embedded environment.

Within the agent container, each agent executes in an isolated execution environment, which not only ensures agent autonomy, but also robustness as each agent can be managed as an individual process. The agent model was developed to take advantage of the underlying SunSPOT API power management features, so the device automatically enters shallow sleep mode to conserve energy when no agent behaviors are executing.

B. Communication

FIPA have published a number of standards with which to develop multi-agent systems, including those for agent communication which define message transport protocols, communicative acts and content languages. These protocols combine to create a rich set of communication tools, however they do introduce significant overheads to message payloads.

Within broadband networks, these overheads typically have an insignificant impact on the operation of the overall system, as both bandwidth and energy are plentiful. However, within a wireless sensor network this is generally not the case, as devices are battery operated, therefore communications must be highly optimized. FIPA has published bit-efficient representations of certain protocols [9], which replace the string representation of each keyword with an equivalent two-byte code. Helin et al. [12] have shown that these are preferable for use within wireless environments. However, this work focussed on high-power devices with a regular charging cycle such as a PDA or cell phones. For lower-power devices such as wireless sensor networks, even the bit-efficient FIPA protocols are still too verbose so another communication scheme should ideally be used that is tailored for optimized energy usage.

The SubSense platform uses an alternative messaging system, based upon the Active Message model and popularized for sensor network use within the TinyOS sensor network platform [13]. This system follows a reactive event-based model, where each data packet has a specific code representing the payload type. Agents register their interest in a particular message type and are supplied with the appropriate incoming message payload whenever a new message is received. The reactive, event-based system is far simpler than the FIPA protocol stack, therefore interaction between the two systems must be handled by a sensor network gateway, which is described below.

IV. SENSOR NETWORK GATEWAY

The sensor network gateway provides an interface between the FIPA-based multi-agent system and the wireless sensor network. It consists of a FIPA-compliant gateway agent and a physical sensor node configured to act as a basestation at the edge of the sensor network. It fulfils two of the high-level roles described in section II: it is both a data provider and an external interface. The gateway agent's primary purpose is to translate between FIPA ACL and bit-efficient messaging, whilst abstracting all sensor network functionality into a set of standardized agent services.

Message translation is carried out using an ontology map, which maps each message type to a particular ontology concept. Within the condition monitoring architecture, the interface agent role includes an ontology map tool which allows foreign data types to be mapped to ontology concepts. This was reused and adapted for the sensor network gateway. Sensor network messages store the data type as a 16-bit integer, which is more efficient than sending a string representation, although as the type is encoded as an integer it requires a translation table to be kept within the sensor network gateway. Currently the ontology mapping needs to be managed manually, although in the future this will be integrated with a centralized model of the sensor network, described in Section V-B2.

Within a wireless sensor network, transmitting and receiving data is the largest consumer of energy, so efficient sensor networks must employ bit-efficient messaging to optimize data transmission. Sensor network traffic must be highly optimized, therefore static information relating to sensory data, such as the plant under observation, should not be transmitted with each measurement. optimizing message payloads lowers energy consumption, but in removing data, this leads to received messages losing some of their associated meaning. This presents an issue when data is received by the sensor network gateway, as key elements may be missing that provide context to the measurement value.

For instance, if an oil temperature measurement is received by the gateway, it may only include the measured value, timestamp, and source address of the sensor node. An agent that calculates top-oil temperature is not necessarily concerned with the details of the physical sensor node which took the measurement, but it will be interested in exactly which transformer the measurement originated from. It is therefore necessary to add relevant information to incoming data packets upon reception at the sensor network gateway, so that analysis and interpretation may be carried out in context.

Currently within the multi-agent CM architecture, plant and sensor information is provided to each agent in the form of an SQL file at runtime which is loaded into each agent's database-backed knowledgebase. If a general-purpose theorem prover service was provided that can answer arbitrary quesions against assertions within its knowledgebase, it could not only provide contextual information to the sensor network gateway, but also provide a generic service to other agents within the community to replace the currently used approach. By storing plant information centrally, agents can be programmed to search for plant information periodically, removing the need to supply them directly with prerequisite site-specific knowledge. A proposal for such an agent is given in the following section.

V. NETWORK MODEL AGENT

A novel approach to message translation and contextualization is proposed, in the form of a network model agent. This agent must be able to: 1) re-use existing domain knowledge on power system resources and the sensor network, and; 2) provide this domain knowledge to the sensor network gateway so it may contextualize incoming sensor data to be understood by other monitoring agents. This could involve translating a sensor network address to a power network asset location. Additionally, the agent should be able to provide this knowledge to other agents within its community as a general-purpose service.

For multi-agent systems to be fully flexible, they must be able to respond to any message that they receive. FIPA-compliant agents typically use a first-order logic formalization as a content language, such as FIPA-SL [9]. For a fully capable agent, these logic statements should be evaluated directly. One method that can be used to achieve this is through the use of a backward-chaining reasoner, or theorem prover.

Theorem provers operate by solving proofs of logic statements containing well-formed formulas that comply to some previously known world model. A suitably capable theorem prover is able to answer arbitrary logic questions against its knowledgebase, so long as its models are valid and it can evaluate each predicate appropriately. It is proposed that the network model agent embodies such a capability, combining a theorem prover with models of the electrical and sensor networks, with appropriate links between the models. A proposal of the network model agent functions are laid out in the following sections, within which ontology concepts are denoted in italics.

A. Reasoning Capabilities

There are several theorem prover implementations documented in the literature, spread across a wide range of languages and logic formalizations. A practical theorem prover implementation for a JADE agent must: 1) be written in a language suitable for implementing predicates defined in the domain ontology, and; 2) support one of the logic formalizations supported by the FIPA content language specifications [9]. The multi-agent condition monitoring architecture uses FIPA-SL as its content language, due to it being the first FIPA content language being ratified as an official IEEE standard.

Fikes et al [14] have developed the Java Theorem Prover, which combines backward-chaining reasoners with an object-oriented knowledgebase. It is content language agnostic, and supports first-order predicate logic in the form of KIF, which has a similar syntax to FIPA-SL. The Jade Semantic Addon [15] is a belief-desire-intention (BDI) reasoning framework for JADE that contains a backwards-chaining reasoner and natively supports FIPA-SL. Its developers claim that its semantic agents can automatically answer queries on any knowledge in its knowledgebase. It is therefore a strong candidate for implementing a theorem prover, although a closer study is required to fully establish its suitability.

B. Agent Functions

The network model agent's primary function is to provide data contextualization to the sensor network gateway; to effectively implement this, it must combine reasoning capabilities with models of the sensor network and electrical network, reusing existing domain knowledge where appropriate. The agent's proposed functions are described as follows.

1) Data Contextualization: Each message received by the sensor network gateway includes a 64-bit IEEE 802 MAC address, unique for each sensor node. Assuming each sensor node is monitoring a single power system resource, the MAC address of the node may be used to query against a model of the sensor network to establish which piece of plant the sensor is attached to (in fact, in a full deployment, there may be multiple nodes monitoring a single resource). A diagram illustrating this agent interaction can be seen in Figure 2. In this interaction, the sensor network gateway asks for plant information pertaining to a particular MAC address. The theorem prover will then construct a number of reasoning steps and iterate through them until a solution is found. In this case, the theorem prover returns a solution to the query, detailing the plant under observation. This fact can then be sent in reply to the sensor network gateway, so it may combine the response with the sensor reading to contextualize the data.

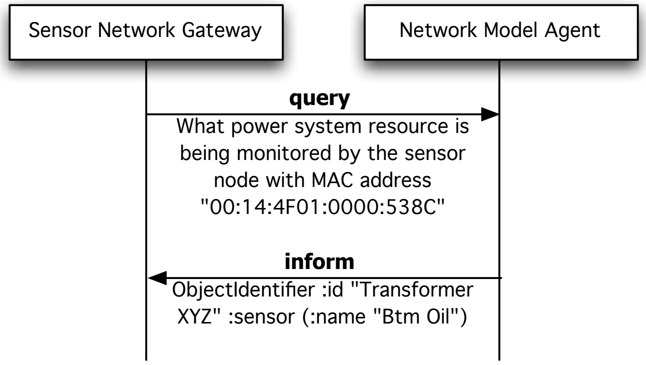

Fig. 2. Interaction diagram showing sensor network querying network model information for component information based upon a sensor node MAC address.

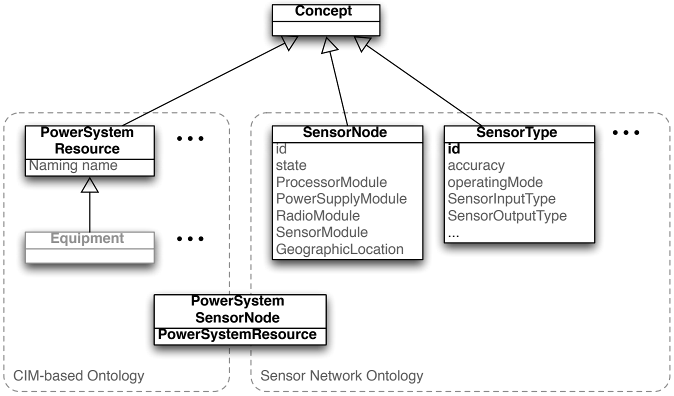

Fig. 3. Class hierarchy of the CIM-based and sensor network ontologies. An additional concept was created to bridge the two models, and an additional slot was added to the *SensorType* class to support multiple sensors per node.

2) Model Reuse: The multi-agent CM architecture was designed with reuse and re-usability as a primary requirement, and therefore uses an upper ontology based upon the Common Information Model (CIM). CIM was designed to harmonise the exchange of power system data between utilities, defining both the syntax and semantics required to build comprehensive electrical network models in a standard format. To exploit the advantages of model reuse, the network model agent may be able to act as a proxy to CIM models, providing an interface to a pre-existing knowledge source.

CIM does not include concepts for sensor nodes, therefore it is necessary to integrate a separate sensor network ontology. Rather than design a new ontology from the ground up, an existing ontology was chosen. The advantages of this are twofold: firstly, the modelling process is time consuming, so reusing an ontology removes this step, and; secondly, other agent systems that were to use the same ontology would be compatible. There have been a number of ontologies for sensor networks proposed, with the most complete of these being that of Avancha et al. [16]. To link this ontology with the CIM-based ontology, it was necessary to identify exactly where they must intersect, as illustrated in Figure 3. To reference each of the ontologies, when deployed, wireless *SensorNode*s are attached to and monitor *PowerSystemResource*s, which not only include high voltage *Equipment*, but also include *Substation*s, in the case of ambient temperature sensors.

To enable the ontologies to be linked, a *PowerSystemSensorNode* concept was created that extends the *SensorNode* concept, containing an addition slot for a *PowerSystemResource* instance. In its original form, the sensor network ontology does not support multiple sensors belonging to a single sensor node, therefore the authors propose an additional *id* field should be added to the *SensorType* concept, which will allow multiple individual physical sensors per node to be defined and discriminated.

VI. CASE STUDIES

To demonstrate the integration of the condition monitoring systems, two case studies are presented. The first describes an implementation of a laboratory demonstrator designed for temperature and vibration monitoring, and the second describes a proposal for an extension to an existing deployment at a UK transmission substation, which would complement the current suite of sensors with a partial discharge detector designed for wireless sensor network applications.

A. Temperature and Vibration Monitoring

A temperature and vibration monitoring demonstrator using the SubSense platform was built within a laboratory environment and integrated with the agent-based condition monitoring architecture described previously. This system is applicable to substation condition monitoring as it may be applied to monitoring ambient substation temperature, as well as insulating oil temperature. Accelerometers, used for vibration sensing, are not typically used although such sensors may be used to monitor the operation of mechanical components that are not generally monitored such as pumps and fans. During laboratory tests, the on-board sensors on the sensor node were used, although for an industrial deployment external sensors would be connected to the device input/output (I/O) bus for more accurate monitoring of plant components.

The systems were integrated using the sensor network gateway to allow real-time sensor data to be displayed within the engineer's interface. In lieu of a full network model agent, mock sensor and plant information was provided to the sensor network gateway at runtime, allowing data contextualization to be carried out statically.

Two reactive application agents were deployed on the SunSPOT to provide data capture and archival functionality. A diagram showing the architecture and data flow is shown in Figure 4. The system includes a temperature and vibration monitoring agent which fulfils the role of data provider, wrapping temperature and vibration drivers as well as providing a data storage facility. The agent periodically samples the on-board temperature and acceleration sensors, then persists both measurements to "Temperature" and "Vibration" record stores in flash memory. A data director agent monitors these record stores for new data, which it forwards to the sensor network gateway.

Upon reception by the gateway agent, each reading is converted to an ontology fact according to the packet type.

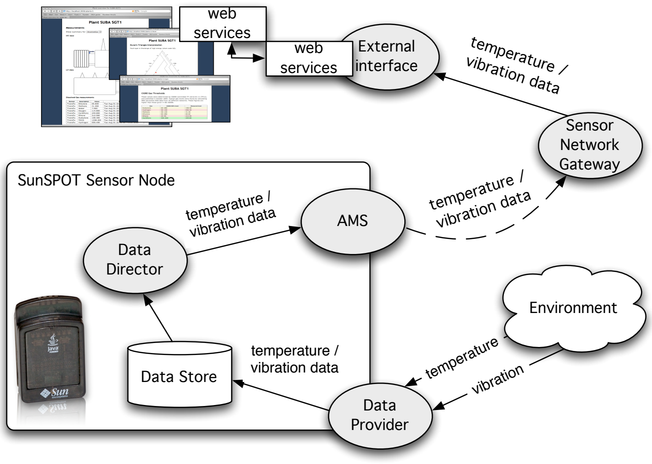

Fig. 4. Agents, communication paths, and system architecture for a wireless temperature and vibration monitoring system

The MAC address is read from the packet, and relevant plant information is returned from a lookup table which is then combined with the sensor data and stored in a local knowledgebase. The gateway implements the "MeasurementProvider" service, which is registered with the Directory Facilitator to allow other agents to search for *Measurement* facts. Periodically, measurement values are requested by a "User Interface" agent, which makes them available to engineers through a web-based application.

This case study demonstrates how a sensor network may be integrated with an agent-based monitoring system to display temperature and vibration data to monitoring engineers. This simplified example uses a static knowledgebase for plant information, which does not require the network model agent or a sensor network ontology. The translation process is simple, but inherently inflexible as the knowledgebase cannot handle arbitrary queries and has to be updated manually. A more complex case is described in the next section, which explains the use of the network model agent for a more flexible approach.

B. Partial Discharge Detection

An industrial demonstrator comprising of a wired multi-sensor system has been deployed within a transmission substation in the UK. This sensor deployment is connected to the agent-based condition monitoring architecture through a web-service interface, to provide access to 45 temperature, vibration, and current sensors on two 180MVA transmission transformers. This case study proposes requirements to extend this deployment with a low-power wireless partial discharge (PD) detector. Partial discharges occur in high voltage plant due to a breakdown in the dielectric insulation, and can be monitored to identify defects before a serious fault occurs. A PD detector developed which uses a frequency-based technique to differentiate between PD RF emissions by comparing the relative energies across 3 frequency bands, results of which are presented in [17]. The detector connects to a SunSPOT wireless sensor node to create an integrated agent-based condition monitoring sensor, capable of automatic interpretation by means of a C4.5 classifier agent running on the sensor node.

When a partial discharge measurement is captured by the detector, the C4.5 agent attempts to classify the defect and generate a fault classification. This summarized representation of the data is then transmitted to the sensor network gateway where it is converted to an ontology fact. Again, the MAC address of the source sensor node will be used to query the details of the plant under observation, although in this case, the network model agent will be used to establish plant information pertaining to the fault classification. This agent will not only aid in the integration of the two platforms, but also provide a central repository for plant information which can used by other agents, adding extra flexibility and functionality to the existing system.

With support for interpreted data provision, the gateway agent is able to forward the fault classifications to other agents, adding support for PD detection and classification to the currently-deployed installation. The condition monitoring architecture includes an Archive Agent, which provides a persistent knowledgebase to the entire agent system. PD classifications from the wireless detector are stored within this archive along with other monitoring diagnoses, and made available to engineers through the same web interface described in the previous section.

This case study has demonstrated a second application of the SubSense platform integrated with an agent-based condition monitoring system. This application requires the addition of the network model agent, as well as an additional behavior to support interpreted data. Both case studies demonstrate that the SubSense architecture can be reused for different applications, and integrated with an agent-based monitoring system.

VII. CONCLUSIONS AND FURTHER WORK

This paper has described the steps required to integrate a wireless sensor network with a FIPA-based multi-agent condition monitoring system. The authors have demonstrated that in doing this, it is possible to extend multi-agent systems down to the sensor level. To integrate these systems, an implementation of a sensor network gateway has been demonstrated, which translates between bit-efficient sensor network data to FIPA-compliant messaging. The issue of data contextualization at the sensor network gateway has been addressed; for laboratory applications this may be carried out using a lookup-table approach, although looking forward a more flexible approach can be taken in the form of a novel network model agent which combines a theorem prover with models of sensor and electrical networks. This agent will be able to answer arbitrary questions on both networks as a general-purpose service to the entire multi-agent condition monitoring system.

A full implementation of the network model agent will be developed which will implement all of the features described in the paper. The theorem proving capabilities of the agent will require a suitable engine to be integrated, which will be carried out after further investigation.

Two case studies have been presented to illustrate different scenarios in which the system may be employed; the first being a laboratory-based temperature and vibration monitoring system, and the second being a proposal for an extension of an existing industrial demonstrator within a UK transmission substation. The case studies have demonstrated reusability and flexibility of the architecture. The system will be developed further, with a view towards an industrial deployment in the future.

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