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REMOTE AREA MODULAR MONITORING SYSTEM FOR FACILITIES AND TRANSPORT

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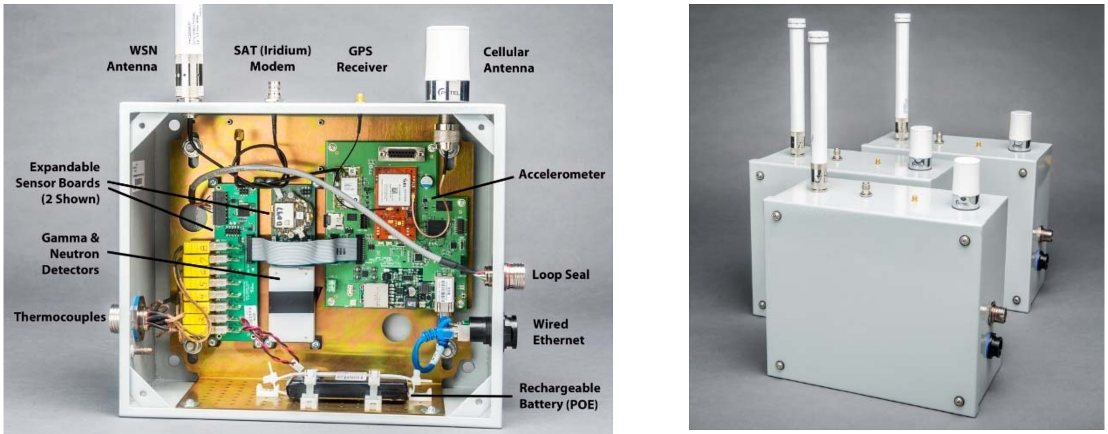
ABSTRACT

ARG-US ("Watchful Guardian") Remote Area Modular Monitoring (RAMM) is an expandable, adaptable system for monitoring critical nuclear plants and facilities, from fuel manufacturing, reactor operation, and spent fuel storage to transportation, reprocessing, and disposal, as well as decommissioning and decontamination. The RAMM architecture is designed with particular emphasis upon (1) modularity and expandability of sensors, (2) multiple communication platforms and protocols, (3) redundant power supply systems, including Power over Ethernet and a rechargeable battery, and (4) a wireless sensor network (WSN) that is self-forming, or self-healing, in disruptive events such as occurred at Fukushima in March 2011. This paper describes the "modular" design philosophy and implementation strategy of RAMM and its unique characteristics. It addresses the RAMM hardware architecture design, the WSN, the embedded application software architecture, and two application examples in facility and transportation monitoring, with preliminary results obtained in recent field testing of the RAMM systems at Argonne National Laboratory.

INTRODUCTION

The ARG-US Remote Area Modular Monitoring (RAMM) System has been developed by Argonne National Laboratory for the U.S. Department of Energy Packaging Certification Program, Office of Packaging and Transportation, Office of Environmental Management. The Packaging Certification and Life-Cycle Management Group at Argonne is one of the pioneers in utilizing radio frequency identification (RFID) technology to enhance the safety, security, and safeguards of nuclear and other radioactive materials during storage and transportation. The ARG-US RFID system is an active RFID system consisting of readers and battery-powered sensor tags. The reader communicates with the tags, which are attached to drum-type packages containing nuclear and other radioactive materials in storage or transportation. Communication between the reader and tags is via 433.9-MHz radio waves and implements the ISO/IEC ISO 18000-7: Information technology—Radio frequency identification for item management—Part 7: Parameters for active air interface communications at 433 MHz. The tags are battery-powered so that each of them can carry a suite of sensors, which provide remote, wireless data communication with the reader so long as they are within the read range (~100 m) of the reader; direct line of sight is not required. All RFID tags communicate only with the reader, not with each other, in a star topology where the reader collects sensor data from the tags at programmed intervals and receives tag-initiated alarms when any of the preset sensor thresholds is violated. The complete suite of sensors in the RFID tag includes those for temperature, humidity, physical shock, tactile seal, radiation (gamma and neutron). and electronic loop seal [1-4].

RAMM was conceived to mitigate the deficiencies in situational awareness noted after the Japanese Fukushima accident when the landline-based surveillance assets were lost [5]. Leveraging ARG-US RFID sensor technology, Argonne designed RAMM to have a two-layered architecture: a wired Ethernet base layer and a wireless sensor network (WSN) overlay. The WSN links multiple robustly built RAMM nodes, each with its unique sensory and communication provisions for the assigned tasks in the application environment. Figure 1(a) is a prototype RAMM unit with the interior exposed to show various sensors, power supplies, and communication antennae; Figure 1(b) is a closed view of three contractor-manufactured RAMM units, all of which are shown without connections to the external sensors, i.e., electronic loop seal, thermocouples, wired Ethernet cable, the satellite Iridium antenna, and the GPS receiver [6].



(a) (b)

Figure 1. (a) RAMM unit, shown with interior exposed, and (b) closed view of contractor-manufactured RAMM units, shown without external connections

Each RAMM unit is controlled by a single board computer (SBC) and carries a suite of sensors with multiple communication interface protocols. A RAMM system is scalable—the monitoring area and communication distance of the system can be extended by adding additional RAMM units—and it is not limited by the radio frequency (RF) communication distance as is the ARG-US RFID/reader system. The following sections describe the RAMM hardware architecture design, the WSN, the embedded application software architecture, and two application examples of RAMM in facility and transportation monitoring. Preliminary results are presented because field testing of the RAMM systems at Argonne only began recently, in 2016.

RAMM HARDWARE ARCHITECTURE DESIGN

Figure 2 is a block diagram showing the hardware architecture design of a RAMM unit. Each RAMM unit consists of 4 main modules: SBC, sensor modules, communication modules, and the power supply system. The modular design makes a RAMM unit flexible in existing applications and easily expandable for system development and future applications.

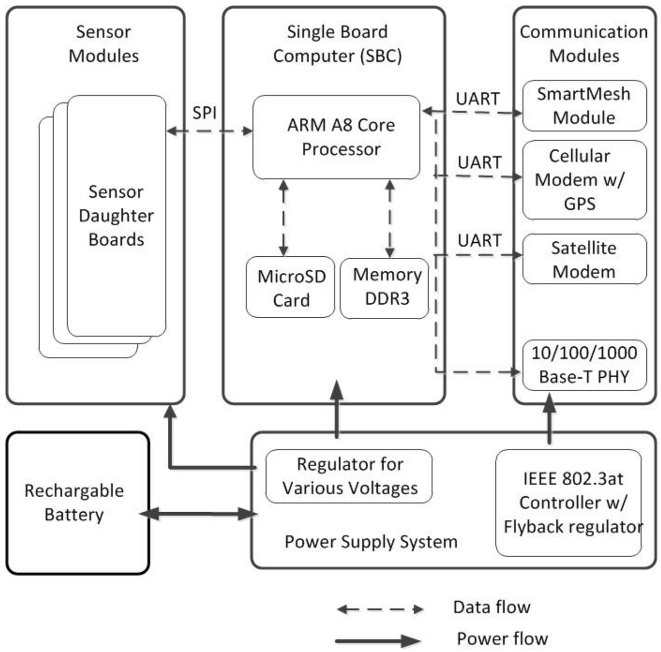


Figure 2. Block diagram of hardware architecture design of a RAMM unit

The SBC is the controller of the RAMM unit, and consists of an ARM A-8 core processor, a 4GB/8GB microSD card, and 512 MB of DDR3 SRAM memory. The abundant computational resources make it possible to support a full-blown operation system (OS) on the SBC. Currently, Ubuntu Trusty is the OS of the SBC, and ithas ported a set of interface drivers enabling control of various peripherals options for the SBC, e.g., Ethernet, Universal Serial Bus (USB), Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C), and Universal Asynchronous Receiver/Transmitter (UART). The OS also contains tools that support remote application debugging, using Eclipse, which facilitates embedded code development for RAMM.

The sensor elements in a RAMM unit are distributed on different sensor daughter boards and the SBC board. Each sensor daughter board is controlled by a microprocessor that communicates with the SBC using the SPI protocol (see Fig. 2). It sends measured sensor values to the SBC and receives from it the control commands and operation parameters, e.g., sensor threshold values. Currently, each RAMM unit has 2 sensor daughter boards: a radiation sensor board carrying a gamma dosimeter and a neutron detector, and a thermocouple board that has provisions for eight (8) external Type-K thermocouples and an electronic loop seal. In addition, the present embodiment incorporates a three-axis accelerometer and a thermistor on the SBC board. Because specialty sensor elements are incorporated into a RAMM unit via sensor daughter boards, they can be added to or removed from a RAMM unit according to the application environment, without any architectural change in the hardware.

Multiple communication modules in a RAMM unit enable it to communicate with a data server application using different channels, when necessary: In normal operation of the RAMM system, the 10/100/100 Based-T Ethernet connection allows each RAMM unit to send data and receive control commands and operation parameters through land-based internet (IT) infrastructure at a comparatively high data transmission rate. In off-normal operation, the cellular and satellite modem, on the other hand, allow a designated RAMM unit to communicate with a data server application using wireless channels. A SmartMesh IP (SMIP) communication module is present in each RAMM unit, and is used to form a WSN of the RAMM units, which is discussed further in the next section.

Each RAMM unit uses Power over Ethernet (PoE) as its primary source of power (see Fig. 1[a]). The Flyback regulator (see Fig. 2) used in its power supply circuit, LTC4278, conforms to the IEEE802.3at standard; it can deliver 25 W of power from PoE. A RAMM unit can also be powered by a rechargeable lithium battery mounted inside the chassis (see Fig. 1[a]). A charging circuit is used to keep the battery fully charged via PoE. The source of power is automatically switched to the battery when PoE is not available, such as during a natural or man-made disruptive event.

WIRELESS SENSOR NETWORK (WSN)

A SMIP network [7] is one type of WSN. The SMIP communication module in each RAMM unit is used to form a WSN. A SMIP WSN consists of two types of RAMM units, Manager and Motes, shown schematically in Figure 3. The Manager and Motes are similar in that each unit contains sensor modules, SBC, and application software; the major difference, however, is that the Manager has firmware in its SMIP communication module necessary to manage the Motes in the WSN, as well as additional wireless communication capability via cellular and satellite modem. The Motes are connected to the Manager, not physically, but through 2.4-GHz RF links. The solid lines between the nodes indicate "established" wireless/RF communication links. Data from the Motes are relayed to the Manager, and the Manager also serves as the gateway of the WSN to the outside world.

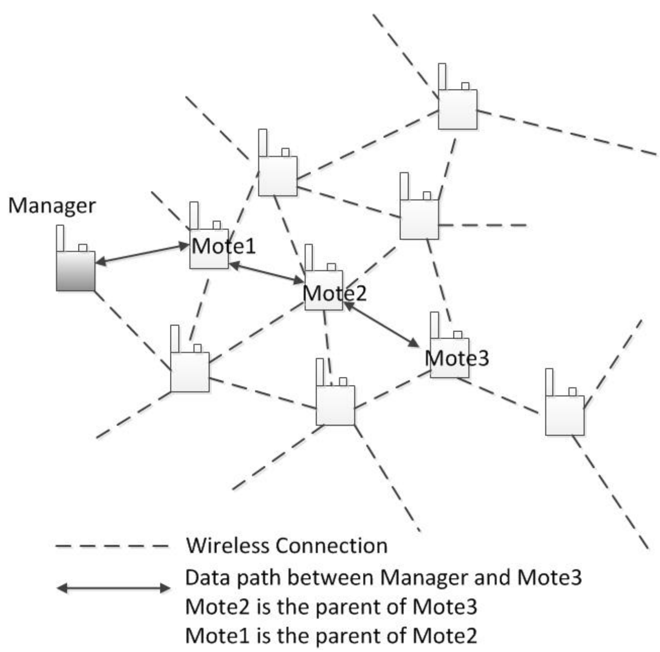


Figure 3. Schematic of a SMIP WSN consisting of one Manager and multiple Motes.

Formation of SMIP WSN

At the beginning of formation of a SMIP WSN, the Manager sends a beacon signal to invite nearby Motes to join the network. Neighboring Motes join the network after they receive the beacon. The term "neighbor" is used to include RAMM units that are within communication range, ~100 m, of each other. The Mote that already joined the network sends a beacon signal of its own to invite its neighbors to join the network. During the joining process, a joined Mote forwards its neighbors' information to the Manager. This joining process continues propagating further away from the Manager. After the initial joining phase is complete, the Manager has information about the topology of the SMIP network. The Manager then assigns routing parents to each Mote, as illustrated in Fig. 3. In a SMIP WSN, the outlying Motes send sensor data to their parents and the parents forward the data until the data reach the Manager. The Manager, as the gateway of the WSN to the outside world, uses its cellular or satellite modem to send the sensor data supplied by the Motes to a remote data server application.

The topology of a SMIP WSN is dynamic; an ongoing discovery process ensures that topological information will be updated if a Mote drops out or is added to the network. This capability, a unique characteristic of WSNs, is often described as "self-healing" or "self-forming." Theoretically, the WSN can be expanded infinitely using the "multi-hops" scheme for data delivery. In practice, the size of a SMIP WSN will be limited by the application environment, as well as the latency incurred on data throughput with increasing numbers of Motes in the WSN, even though multiple Managers can be added to the WSN to provide redundancy and improve performance. Another important characteristic of a SMIP WSN consisting of battery-powered RAMM units is that the data collection and transmission do not require landline-based infrastructure and power sources, making it particularly useful in providing situational awareness during disruptive events.

APPLICATION SOFTWARE ARCHITECTURE

In each RAMM unit, the application software runs on its SBC to orchestrate different functions of the underlying hardware. Figure 4 is a schematic of the hardware interface and application software architecture, which has been greatly simplified to show only two layers: Main Module and Hardware Drivers. A major portion of the Main Module layer is built using functions ported by the Hardware Drivers layer below it in the software architecture hierarchy. For example, the hardware driver for the satellite modem contains functions that enable a RAMM unit to connect to the satellite modem using the UART protocol (see Fig. 2), whereas the drivers for the sensor daughter boards contain functions that connect the Main Module code to two SPI ports of the SBC, through which the Main Module can collect data from the sensor daughter boards. The Main Module also uses the SPI ports to send commands to the sensor daughter boards to configure their operation parameters, such as sensor thresholds.

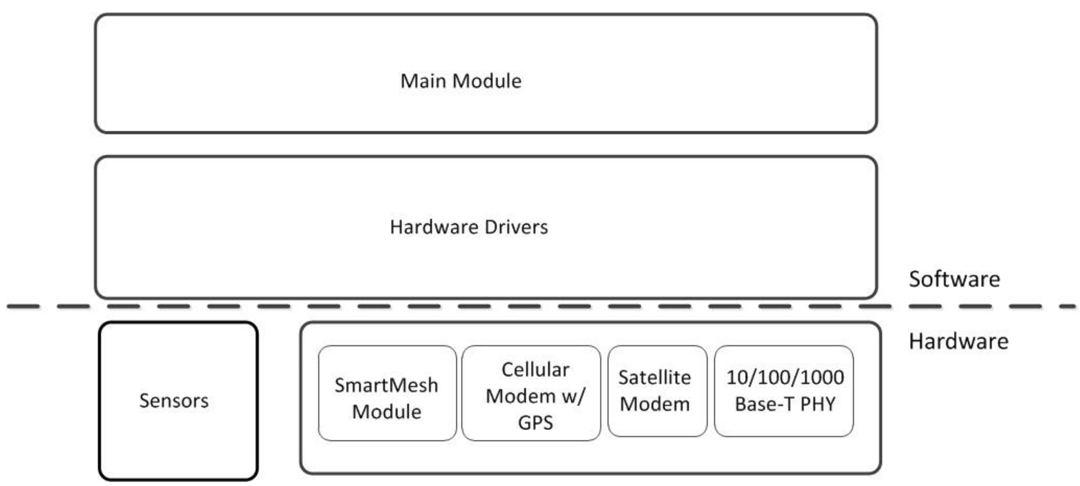


Figure 4. Application software architecture and hardware interface of a RAMM unit

The two-layer application software architecture is designed to make the RAMM system robust and flexible enough to accommodate the evolving needs of future applications. While the Main Module may need to be modified for new application environments, the functions in the hardware drivers remain unchanged. Both the Main Module and the Hardware Drivers software are written in ANSI C++ language. An Eclipse integrated development environment (IDE) is used for code development with a remote debugger.

APPLICATION EXAMPLES

Two application examples of RAMM are briefly described below. Only preliminary results are presented here, as field testing of the RAMM systems at Argonne just began and will continue through the remainder of 2016.

Facility Monitoring

A small-scale SMIP WSN, consisting of seven RAMM units (one Manager and six Motes), was configured in 2016 for field testing in an office building at Argonne. A single prototype RAMM unit was also recently installed in Argonne's Alpha Gamma Hot Cell Facility (AGHCF) for field testing and comparison with the existing ARG-US RFID system deployed in the AGHCF since August 2013 [8]. Figure 5 shows the web pages of two RAMM units, (a) Unit #2104 (Manager) and (b) Unit #1105 (Mote), with their sensor values displayed by clicking the corresponding symbols on the web pages. Manager Unit #2104 and Mote Unit #1105 have the same set of sensors but show slightly different temperature readings: 23°C for Manager Unit #2014 vs. 22°C for Mote #1105, which is mounted near the building exit staircase. The thermistor inside Manager Unit #2104 registered 36°C, which is slightly lower than the 38°C registered by the thermistor inside Mote Unit #1105.

(a) (b)

Figure 5. Web pages of RAMM Units (a) #2104 (Manager) and (b) #1105 (Mote) in a small-scale SMIP WSN in an office building at Argonne

All of the RAMM units in the small-scale SMIP WSN are currently connected to building power via PoE. A test plan is being prepared by "randomly" disabling the PoE of the RAMM units to evaluate the system response of the SMIP WSN. The WSN performance under various scenarios will be reported in future publications in 2017.

Transportation Monitoring (Traveler)

Transportation monitoring is another potential application of RAMM, particularly a RAMM Manager equipped with cellular and satellite modems powered by a rechargeable battery. The web page in Figure 6 shows RAMM Unit #2103 in a vehicle in a parking lot on the Argonne campus; the sensor data are displayed by clicking the symbol at the lower left corner of the web page. RAMM Unit #2103 is powered by a rechargeable lithium battery and communicates with a remote data server application via cellular and satellite channels. The GPS receiver in the cellular modem (see Figs. 1[a] and 2) provides the real-time location of the vehicle; the latitude and longitude coordinates are revealed by clicking the vehicle icon on the map display.

Figure 6. Web page of RAMM Unit #2103 in a vehicle parked in an Argonne parking lot

A test plan is also being prepared for field testing of RAMM units in single- and multi-vehicle transportation applications. Of particular interest is the comparison of RAMM performance vis-à-vis the ARG-US RFID/ CommBox and CommBox-mini described in a companion paper by Craig et al. for PATRAM 2016 [9].

SUMMARY

ARG-US ("Watchful Guardian") Remote Area Modular Monitoring (RAMM) is an expandable, adaptable system for monitoring critical nuclear plants and facilities, from fuel manufacturing, reactor operation, and spent fuel storage to transportation, reprocessing, and disposal, as well as decommissioning and decontamination. The ARG-US RAMM architecture is designed with particular emphasis upon (1) modularity and expandability of sensors, (2) multiple communication platforms and protocols, (3) redundant power supply systems, including Power over Ethernet and a rechargeable battery, and (4) a wireless sensor network that is self-forming, or self-healing, in disruptive events such as occurred at Fukushima in March 2011. The "modular" design philosophy and implementation strategy of RAMM are described, along with the unique characteristics of the RAMM hardware architecture design, the WSN, and the embedded application software architecture, and two application examples in facility and transportation monitoring. Test plans are being prepared for field testing and applications of ARG-US RAMM systems at Argonne and elsewhere in the near future.

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